



COLLEGE OF ENGINEERING, MATHEMATICS AND PHYSICAL SCIENCES

Hierarchical Multi-Project Planning and Supply Chain Management: an Integrated Framework

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ABSTRACT

This work focuses on the need for new knowledge to allow hierarchical multi-project management to be conducted in the construction industry, which is characterised by high uncertainty, fragmentation, complex decisions, dynamic changes and long-distance communication. A dynamic integrated project management approach is required at strategic, tactical and operational levels in order to achieve adaptability.

The work sees the multi-project planning and control problem in the context of supply chain management at main contractor companies. A portfolio manager must select and prioritise the projects, bid and negotiate with a wide range of clients, while project managers are dealing with subcontractors, suppliers, etc whose relationships and collaborations are critical to the optimisation of schedules in which time, cost and safety (etc) criteria must be achieved.

Literature review and case studies were used to investigate existing approaches to hierarchical multi-project management, to identify the relationships and interactions between the parties concerned, and to investigate the possibilities for integration. A system framework was developed using a multi-agent-system architecture and utilising procedures adapted from literature to deal with short, medium and long-term planning. The framework is based on in-depth case study and integrates time-cost trade-off for project optimisation with multi-attribute utility theory to facilitate project scheduling, subcontractor selection and bid negotiation at the single project level. In addition, at the enterprise level, key performance indicator rule models are devised to align enterprise supply chain configuration (strategic decision) with bid selection and bid preparation/negotiation (tactical decision) and project supply chain selection (operational decision). Across the hierarchical framework the required quantitative and qualitative methods are integrated for project scheduling, risk assessment and subcontractor evaluation. Thus, experience sharing and knowledge management facilitate project planning across the scattered construction sites.

The mathematical aspects were verified using real data from in-depth case study and a test case. The correctness, usefulness and applicability of the framework for users was assessed by creating a prototype Multi Agent System-Decision Support System (MAS-DSS) which was evaluated empirically with four case studies in national, international, large and small companies. The positive feedback from these cases indicates strong acceptance of the framework by experienced practitioners. It provides an original contribution to the literature on planning and supply chain management by integrating a practical solution for the dynamic and uncertain complex multi-project environment of the construction industry.

Keywords: hierarchical multi-project planning, supply chain management, uncertainty, complexity, adaptive systems, multi agent system architecture, decision support system, MAS-DSS, optimisation, time-cost trade-off, GDTCTP, DMPSP, construction industry.

DEDICATION

I would like to dedicate this PhD thesis to the loving memory of my mother and to the memory of my father who was a teacher.

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TABLE OF CONTENTS

ABSTRACT	2
DEDICATION	3
ACKNOWLEDGMENT	4
TABLE OF CONTENTS	5
GLOSSARY OF TERMS	9
LIST OF FIGURES.....	11
LIST OF TABLES	13
LIST OF PUBLICATIONS.....	15
CHAPTER 1 INTRODUCTION.....	16
1.1 Introduction.....	16
1.2 General definitions.....	17
1.2.1 What is a Project?.....	17
1.2.2 Project Management.....	18
1.2.3 Multi-project management.....	18
1.2.4 Dynamic and uncertain environment.....	19
1.2.5 Complexity.....	20
1.3 Area of research in project management.....	22
1.4 Statement of the problem	23
1.5 Objectives	24
1.6 Research Methodology	25
1.6.1 Literature review	28
1.6.2 In-depth Case study	28
1.6.3 Constructing the integrated framework and its required procedures.....	30
1.6.4 Validation and feedback from the first case study	31
1.6.5 Adopting solution algorithm, testing the model and verification of proposed solution.....	32
1.6.6 Improving the framework.....	32
1.6.7 External Validation	32
1.7 Structure of the thesis	33
CHAPTER 2 HIERARCHICAL MULTI-PROJECT MANAGEMENT.....	36
2.1 Introduction.....	36
2.2 Basic characteristics of project planning and scheduling	37
2.2.1 Activity and network characteristics	37

2.2.2	Resource types	37
2.2.3	Project scheduling objectives.....	38
2.3	Hierarchical multi-project planning.....	38
2.3.1	Hierarchical construction multi-project planning	44
2.4	Risk in project portfolio management.....	45
2.4.1	Assessing and Quantifying risk in construction management.....	46
2.5	Supply chain in multi-project environment	48
2.5.1	Supply chain coordination (execution-oriented studies).....	50
2.5.2	Supply chain configuration (design-oriented studies).....	54
2.6	Project selection in multi-project management.....	62
2.7	Summary	66
CHAPTER 3 MULTI-PROJECT SCHEDULING		68
3.1	Introduction.....	68
3.2	Single-Project scheduling.....	69
3.2.1	Single-mode problem.....	71
3.2.2	Multi-mode RCPSP	71
3.3	Centralised multi-project scheduling (traditional approach)	75
3.4	Decentralised multi-project scheduling problem (DMPSP).....	79
3.4.1	Why use multi agent methods for DMPSP?	80
3.4.2	Research works in DMPSP	82
3.4.3	Decentralised hierarchical multi-project planning	88
3.5	Investigation on adopting a modelling approach	90
3.6	Summary	92
CHAPTER 4 DYNAMICS, UNCERTAINTY AND COMPLEXITY		93
4.1	Introduction.....	93
4.2	Dynamics.....	94
4.3	Uncertainty	96
4.3.1	Uncertainty and single project scheduling.....	96
4.3.2	Uncertainty and multi-project scheduling	98
4.4	Uncertainty and complexity in construction project portfolio management	99
4.5	Key Performance Indicators.....	103
4.6	DIMS technology, a lesson from manufacturing systems for modelling project portfolio management.....	105
4.6.1	DIMS concept	106

4.6.2	Combinatorial optimization	106
4.6.3	Configuration procedure.....	107
4.7	Lessons learned from DIMS and its required improvements.....	108
4.8	Comparing NSGA2 and DIMS optimisation engine	111
4.8.1	Test case of Iterative bidding process.....	111
4.8.2	Setting up the NSGA2	113
4.8.3	Comparing the results and conclusion	114
4.9	Summary of the adopted models in hierarchical planning	117
4.10	Summary	119
CHAPTER 5	CASE STUDIES IN THE CONSTRUCTION INDUSTRY	120
5.1	Introduction.....	120
5.2	UPP.....	121
5.2.1	Data collection	122
5.2.2	Collected data.....	124
5.2.3	Findings from UPP.....	126
5.3	Other case study companies.....	129
5.3.1	Kayson Inc.	130
5.3.2	Interserve Plc	131
5.3.3	Fanavaran Co.	131
5.4	Summary	135
CHAPTER 6	THE NEW SOLUTION FOR MULTI-PROJECT PLANNING AND SCM.....	136
6.1	Introduction.....	136
6.2	Hierarchical integrated multi-project management framework..	137
6.3	Architecture of the proposed model	140
6.4	The Platform and Blackboard system.....	143
6.5	Communication protocol.....	143
6.6	Relationships and interactions of Agents.....	144
6.6.1	Description of the Roles	146
6.7	Integrated Rule Models in proposed MAS-DSS	151
6.7.1	Bid/Project selection.....	151
6.7.2	Subcontractor Selection	153
6.7.3	Project Scheduling Time-Cost Trade-off with Generalized Precedence Constraints	157
6.7.4	Bid preparation decisions and negotiation with client agent	165

6.7.5	Rescheduling negotiation protocol	172
6.7.6	KPI Rule models	174
6.7.7	Supply chain configuration.....	179
6.8	Summary and discussion on adopted models	181
6.9	Summary	190
CHAPTER 7	EVALUATION OF THE PROPOSED FRAMEWORK.....	192
7.1	Introduction.....	192
7.2	Overview of the MAS-DSS Solution	193
7.3	Some snapshots of the developed MAS-DSS.....	196
7.4	Empirical evaluation of the proposed decision making framework	201
7.4.1	Internal evaluation	201
7.4.2	External evaluation	203
7.5	Overall evaluation and Discussion.....	216
7.6	Summary	220
CHAPTER 8	CONCLUSION.....	221
8.1	Introduction.....	221
8.2	Discussions	221
8.2.1	Investigate existing methods.....	223
8.2.2	Identify relationships and interactions between parties	224
8.2.3	Investigate integration possibilities.....	224
8.2.4	Construct framework and adapt the decision making procedures	224
8.2.5	Validate the feasibility of the proposed approach.....	225
8.3	Major contribution and overall evaluation.....	226
8.4	Recommendations for industry	227
8.5	Limitations	228
8.6	Conclusion and contribution to knowledge	229
8.7	Future research.....	230
Appendix A:	Non-dominated sorting genetic algorithm (NSGA2)	232
Appendix B:	Hans et al.'s (2008) model.....	239
Appendix C:	Arslan et al.'s (2008) model.....	241
Appendix D:	Validation Sheet	242
Appendix E:	Nonparametric test.....	243
References	244

GLOSSARY OF TERMS

AHP	Analytical Hierarchy Process
ANC	Ant Colony Optimization
APD	Average Project Delay
BIM	Building Information Modelling
CCI	Centre for Construction Innovation
CEO	Chief Executive Officer
CFP	Call for Proposal
CI	Construction Industry
CIOB	Chartered Institute of Building
CPM	Critical Path Method
CPSO	Combinatorial PSO
CSC	Construction Supply Chain
CSCM	Construction Supply Chain Management
CW	Collaborative Working
DIMS	Dynamically Integrated Manufacturing System
DMP	Decentralised or Distributed Multiple Projects
DMPSP	Decentralised Multi-Project Scheduling Problem
DP	Dynamic Programming
DPR	Dynamic Programming Relaxation
DRCMPSP	Decentralised Resource Constrained Multi-Project Scheduling Problem
DSS	Decision Support System
DTCTP	Discrete Time-Cost Trade-Off Problem
EPC	Engineering Procurement Construction
ETO	Engineering to Order
FST	Fuzzy Set Theory
GA	Genetic Algorithms
GC	General Contractor
GIFA	Gross Internal Floor Area
HS	Harmony Search
HTML	Hypertext Markup Language
JSSP	Job Shop Scheduling Problem
KPI	Key Performance Indicators
MA	Mediator Agent
MAS	Multi Agent System
MAS-DSS	Multi Agent System- Decision Support System
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MDOT	Michigan Department of Transportation
MOEA	Multi Objective Evolutionary Algorithm

MTS	Make to Stock
OBS	Organisational Breakdown Structure
PA	Portfolio Manager Agent
PM	Project Management
PMAs	Project Manager Agents
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute
PSO	Particle Swarm Optimization
RBS	Risk Breakdown Structure
RBS	Risk Breakdown Structure
RCCP	Rough-Cut Capacity Planning
RCMPSP	Resource Constrained Multi-Project Scheduling Problem
RCPSP	Resource Constrained Project Scheduling Problem
RES	Restart Evolution Strategy
RFB	Request for Bid
RNND	Royal Netherlands Navy Dockyard
SA	Simulated Annealing
SCAs	Subcontractor Agents
SCM	Supply Chain Management
SDI	Structural dynamic Interaction
SME	Small to Medium Sized
TCM	Traditional Construction Management
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TQM	Total Quality Management
TS	Tabu Search
UPP-Ltd	University Partnership Programmes Limited Company
WBS	Work Breakdown Structure
WEBSES	Web Based Subcontractor Evaluation System
WP	Work Packages
XMEC	Exeter Manufacturing Enterprise Centre

LIST OF FIGURES

Figure 1.1 Project Unknowns and dynamic degree of projects (Collyer & Warren, 2009).....	20
Figure 1.2 Interaction patterns in construction (Gadde & Dubois, 2010).....	22
Figure 1.3 The actual research schedule.....	26
Figure 1.4 The overall research method.....	27
Figure 1.5 The literature review process.....	28
Figure 2.1 Hierarchical multi-project planning and control framework (Hans et al., 2007).....	41
Figure 2.2 A systems model of the multi-project environment. (Aritua et al., 2009).....	44
Figure 2.3 Two interrelated layers: single project network and project business network (Artto et al., 2008).....	49
Figure 2.4 An EPC process model (Yeo & Ning, 2002).....	51
Figure 2.5 Model of construction supply chain (Xue et al., 2005).....	51
Figure 2.6 A snapshot of user interface of the agent based system on Zeus platform (a), Multi attribute protocol (b), (Xue et al., 2005).....	53
Figure 2.7 An agent based framework for CSC coordination (Xue et al., 2007).....	54
Figure 2.8 Development of CW in construction projects (Xue et al., 2010).....	55
Figure 2.9 Four types of triads based on the subcontractor's relationship with a third actor.....	57
Figure 2.10 Phases during a typical bidding process (Arslan et al., 2008).....	59
Figure 2.11 Evaluating and selecting sub-contractors using WEBSES (Arslan et al., 2008).....	62
Figure 2.12 The process development (Hsueh et al., 2007).....	65
Figure 3.1 Super-project network (Gonçalves et al., 2008).....	76
Figure 3.2 Multi-Individual project Network (Kurtulus, 1985).....	76
Figure 3.3 A MAS organisation of DMPSP resource, control system (Lee et al., 2003).....	83
Figure 3.4 Multi-agent system functional schema (Confessore et al., 2007).....	84
Figure 3.5 Multi-agent architecture of (Adhau et al., 2012) model.....	87
Figure 3.6 Project and recourse manager agents (Araújo, Pajares, & Lopez-Paredes, 2010).....	89
Figure 4.1 The event-driven procedure of project portfolio scheduling (Kao et al., 2006).....	94
Figure 4.2 Complex adaptive behaviour (Aritua et al., 2009).....	101
Figure 4.3 The relaxation of structural constraints in resource regrouping (step 4) (He, 2011).....	109
Figure 4.4 Parallel job scheduling.....	109
Figure 4.5 Required parts/operations for satisfying laptop orders (Akanle & Zhang, 2008).....	112
Figure 4.6 Iterative bidding process for order 21.....	115
Figure 4.7 NSGA2 solutions.....	115
Figure 6.1 Hierarchical integrated multi-project planning framework.....	138
Figure 6.2 Multi-Agent architecture of the multi-project planning and supply chain management.....	140

Figure 6.3 Complex dynamic construction multi-project system	145
Figure 6.4 The integrated bidding process, subcontractor selection and project scheduling model	155
Figure 6.5 Pareto-front solutions obtained by NSGA.....	164
Figure 6.6 Project schedule (for project duration 75, project total cost 45500).....	165
Figure 6.7 Rescheduling negotiation protocol.....	173
Figure 6.8 Construction predictability time (Prisk, 2011).....	178
Figure 6.9 Adapted models embedded in the framework	182
Figure 7.1 Integrated MAS-DSS models for construction multi-project management	194
Figure 7.2 Defining portfolios	196
Figure 7.3 Defining projects and their work packages.....	197
Figure 7.4 Defining trades and scoring them	197
Figure 7.5 Selecting the SCs based in their score and sending RFB electronically	198
Figure 7.6 Automated bidding process.....	199
Figure 7.7 One of the solutions from the Pareto-front Curve and its corresponding Gantt Chart	200
Figure 7.8 Overall evaluation of the proposed framework.....	217
Figure 7.9 Overall evaluation across all the criteria for individual subsystems.....	218
Figure 7.10 Overall evaluation for implementation.....	219

LIST OF TABLES

Table 1.1 Project based organisation (Söderlund, 2004)	20
Table 1.2 SDI Matrix (Whitty & Maylor, 2009)	21
Table 2.1 Hierarchical multi-project planning (Neumann et al., 2003)	40
Table 2.2 Project selection research in the construction industry (developed from Wang et al (2009)	63
Table 3.1 A classification of project scheduling problems (Reyck & Herroelen, 1999)	69
Table 3.2 List of abbreviations (Reyck & Herroelen, 1999)	69
Table 3.3 Summarising the literature review in single project scheduling	74
Table 3.4 Priority rules in heuristic methods	78
Table 3.5 Analysis of existing methods and adopting a modelling approach for multi-project planning.....	91
Table 4.1 Positioning framework for multi-project organisations (Hans et al., 2007)	98
Table 4.2 Different approaches to the (multi-)project scheduling problem (Herroelen & Leus, 2004a)	99
Table 4.3 Summary of the case studies (Tennant & Langford, 2008) and KPIs comparison	104
Table 4.4 Resource options for computers (Akanle & Zhang, 2008).....	111
Table 4.5 Solution obtained from Iterative bidding process (Akanle & Zhang, 2008).....	112
Table 4.6 Solutions by implementing NSGA2 after one run with 30 generations.....	115
Table 4.7 Comparisons between best solutions obtained from two algorithms ..	115
Table 4.8 Summary of the adopted models and the identified gaps that need to be addressed.....	118
Table 5.1 Accommodation blocks ongoing projects at the University of Exeter “pilot study”	124
Table 5.2 Top-level WBS of a student accommodation block.....	126
Table 5.3 Case study companies for external validation.....	129
Table 6.1 Project activities and precedence relationships.....	163
Table 6.2 Alternative activity time cost options	163
Table 6.3 Solutions obtained by exact algorithm Sakellaropoulos & Chassiakos (2004).....	164
Table 6.4 Solutions obtained by NSGA2.....	164
Table 6.5 Non-dominated solutions and guarantee periods set by the PA	169
Table 6.6 Ranked solutions for negotiation purpose based on CA’s preference ..	170
Table 6.7 The best decision based on risk level.....	171
Table 6.8 Customer satisfaction KPI and Business rules set in MAS-DSS for Bid selection	176
Table 6.9 Time predictability KPI and Business rules set in MAS-DSS for supply chain management	179
Table 7.1 Experts who attended in the presentation meeting	201
Table 7.2 the proposed model evaluated by Director of Estate Development of the University of Exeter	205

Table 7.3 List of Experts interviewed in Kayson Inc.	207
Table 7.4 The proposed model evaluated by Kayson Inc.	209
Table 7.5 List of experts interviewed in Interserve Inc.	210
Table 7.6 The proposed model evaluated by Interserve Regional Office in Exeter	210
Table 7.7 List of experts interviewed in Fanavaran Co.	212
Table 7.8 The proposed model evaluated by Fanavaran Co.	215

LIST OF PUBLICATIONS

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CHAPTER 1 INTRODUCTION

1.1 Introduction

The term 'Project' usually refers to one-of-a-kind production where certain types of resources should perform together to achieve the objectives of the project such as time, cost and quality.

Most firms are involved with several projects simultaneously. For companies in industries where projects are the main part of the business, project management is of key importance. Project management is involved with dynamic and complex situations in generally multi-project organisations and particularly for construction companies. For each single project, resources across a supply network are deployed for completing the project with high efficiency, minimum cost and on time. Multi-project companies need a transparent project planning and control system that enables management to know about resource utilization across all projects dynamically. Risk and uncertainty are characteristics of large scale construction projects. The necessity of deploying proper tools and techniques that enable the portfolio managers to accommodate complexity of the business network are real challenges that need to be addressed. The portfolio environment changes dynamically, thus planning and configuring of resources across project networks and also business network are often necessary in order to meet the strategic, tactical and operational objectives.

In addition, when bidding for new projects, management should have an accurate estimation of the cost, while looking at the capacity and the reliability of available resources, particularly in competitive construction projects. Outsourcing in this industry is a common approach and the bidding price and time estimations are tightly related to the subcontractors' estimations of the work packages and their individual bids. Furthermore, since the subcontractors are autonomous business enterprises, uncertainty and risk factors plays a vital role in selecting the right subcontractors from one side and submitting the right bidding price to the clients from the other side.

The performance of each individual project could have either positive or negative impact on the market. These could potentially increase or decrease the amount of the potential future projects for the enterprise.

In this research, the aim is designing a framework and providing a model for hierarchical multi-project management in construction organisations, which involve the entire organisation and its supply network. This framework could assist portfolio and project managers to deal with complexity of the system that usually arises from uncertainty. Therefore, the management could dynamically integrate the complex multi-project system with its associated supply chain in the main contractor organisations. This research will enable managers to cope with the resource constrained multi-project problem and structurally configure subcontractors of the business supply chain simultaneously by looking at the time-cost optimization and feedback learning approach.

1.2 General definitions

For more than half a century, project management has been one of the attractive research topics for both practitioners and scholars. Research work has been conducted to solve planning and scheduling problems in single or multi project environments. Before getting involved with its relevant literature review, it might be a good idea to consider some major definitions.

1.2.1 What is a Project?

The word 'project' entails different aspects to various individuals. There is a common definition of project proposed by the Project Management Institute (PMI) which has been widely accepted by both practitioners and academics. The Project Management Institute (PMI) in its official definition of Project Management Body of Knowledge (PMBOK) defined 'project' as follows:

“A project is a temporary endeavour undertaken to create a unique product, services, or result” (PMI, 2013).

There are some common characteristics in all projects including a goal, uniqueness, complexity, temporary nature, uncertainty, and having a life cycle consisting of different phases.

1.2.2 Project Management

Demeulemeester & Herroelen (2002) argue that project management is a process of several phases including the definition phase, the planning phase, the scheduling phase, the control phase and the termination phase.

There is a consensus that at the first step of planning phase, projects must be broken down into manageable components based upon Work Breakdown Structure (WBS). The target is to partition the project into major pieces (main elements) called work packages, and to recognise the specific activities that need to be performed for each work package so as to achieve the project objective. In this phase, management should think about some changes or even reconfiguration of the business supply chain. Organisational Breakdown Structure (OBS) or project organisation chart shows the various organisational units that are going to work for the project. Demeulemeester & Herroelen (2002) define the relation between WBS and OBS as:

“At the intersection of the lowest WBS and OBS levels we find the so-called work packages in which a lowest unit in the OBS is assigned a specific task in a corresponding lowest unit of the WBS. In operational terms, a work package is the lowest unit of project control. Work packages are further divided into sets of activities and subtasks.”

After recognizing activities through WBS, time and cost estimation could be conducted in planning phase. Scheduling is a process that provides project base plan or baseline plan, which determine the start and finish time of each activity. The control and termination phases are both important to guarantee the goal achievement of the project.

1.2.3 Multi-project management

Söderlund (2004) provided a general framework of all research in the field of project management regarding the organisational aspects and separated these studies into four categories as in Table 1.1. According to this classification, many firms handle more than one project at any instant, which in this research are named as project portfolio or multi-project organisations interchangeably.

A project portfolio is “a group of projects that share and compete for the same resources and are carried out under the sponsorship or management of an organisation. Project portfolio management can be considered a dynamic decision process, where “a list of active projects is constantly updated and revised” (Martinsuo & Lehtonen, 2007). In these companies, Hans et al. (2007) argued that Project Portfolio Management is the main role of executive and senior managers and by attention to strategic medium and/or long-term decisions; it covers project selection and prioritisation of a variety of projects. Meanwhile, multi-project planning is associated with operational and tactical decisions on resource allocation and scheduling. Based on this hierarchy of decision-making, generally project or resource managers have conducted this role. In addition, Hans et al. (2007) believe that a program is a family of related projects, which have only a single goal. Sending a man to the moon could be an appropriate example for this. Therefore, program management is a special case of multi-project management.

1.2.4 Dynamic and uncertain environment

Collyer & Warren (2009) investigated all aspects of dynamic views of project management. They provided a model to define the level of dynamism Figure 1.1. They believed that the level of knowledge for each project makes it dynamic or static although a project can have aspects of both. Furthermore, they argued that the level of knowledge itself rarely guarantees the success of project. In addition, they explained how an “on time” and “on budget” project such as Iridium Production in Motorola for which many billions of dollars was invested was unsuitable for stockholders due to facing many fluctuations in market condition particularly when the project finished and it was ready to produce its products, the technology was rapidly changed and new generation of telecommunication facilities came to the market. In contrast, the “Titanic” movie project, which was poor in the field of planning and control, was highly successful (Collyer & Warren, 2009). Similarly, Manning (2005) believes that the “TV movie industry” could be a template for all dynamic environments which are able to create their own networks dynamically and by using virtual organisations they could reduce their costs significantly.

Table 1.1 Project based organisation (Söderlund, 2004)

		Firm	
		Single	Multi
Project	Single	Project Management	Inter-firm Projects
	Multi	Multi-Project firms	Project ecologies

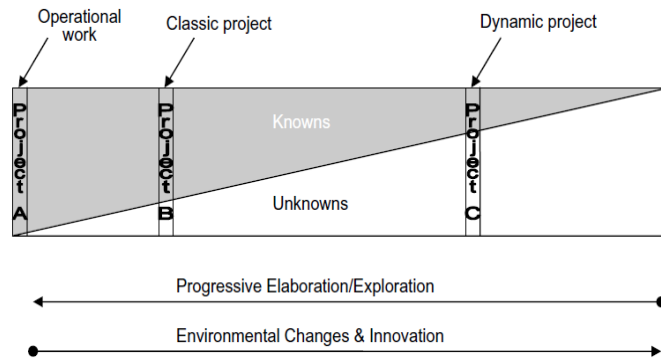


Figure 1.1 Project Unknowns and dynamic degree of projects (Collyer & Warren, 2009)

In Figure 1.1, the grey area is called “known area” where uncertainty and risk is low while the white area is “unknown area”. Unknown area refers to uncertainty and risk where the environment is changed frequently. For instance in Figure 1.1, “Project A might be a production line where there only variable is the colour required. Project B might be a house construction where there are more unknowns at the start but most are resolved in the early stages. Project C might be a software development project for a new business” Collyer & Warren (2009).

According to Ibrahim et al. (2010), at the early stage of construction projects, details of planning are left unclear as situation changes frequently, primary sequences are only partly determined by hard logic, interdependencies are only partly understood due to shared resources and intermediate products. In addition, Artto et al., (2008) pointed out the dynamic environment in the context of multi-project and business supply chain in the construction industry. According to them, “the dynamic interplay between the short-term temporary project supply chain and the permanent (but dynamic and constantly changing) business supply chain is a potential source of uncertainty”.

In brief, uncertainty is one of the unavoidable aspects of the real time project management environment. It causes disturbances in the system and makes it dynamic - planning and control need to be applied dynamically to update the state of the system and to fine-tune to accommodate the disturbances.

1.2.5 Complexity

In multi-project management, “complex” and “complexity” are two terminologies that need to be clarified. Although complexity has been widely studied in various

disciplines, its interpretation in the field of management needs more investigation (Thomas & Mengel, 2008).

Whitty & Maylor (2009) define a complex system as follows: “A complex system is a system formed out of many components whose behaviour is emergent.” It is clear that the behaviour of a complex system could not easily be understood from the manner of its components. They claim that complexity is a measure of the intrinsic complication to attain the appropriate perception of a complex system. They provide a structural dynamic interaction (SDI) matrix as a model of managerial complexity in the project environment as in Table 1.2.

In this matrix, ‘Structural’ is categorised as external stakeholders, task characteristics and organisational complexity. They believe that managerial complexity of the project environment stems from the combination of both individual structural elements and the dynamic effects of changes. The fourth stage of the SDI matrix is completely complex due to having “multiple structural elements interacting and changing as they progress” (Whitty & Maylor, 2009).

Table 1.2 SDI Matrix (Whitty & Maylor, 2009)

	Independent	Interacting
Structural	1. Independent Structural Complexity	2. Interacting structural Complexity
Dynamic	3. Independent dynamic Complexity	4. Interacting dynamic Complexity

Vidal & Marle (2008) proposed a novel framework to define project complexity. They classified project complexity factors into two main types; technological complexity and organisational complexity. They categorised each of these types into elements of context, project system size, project system variety and interdependencies within the projects system.

One of the main reasons for complexity of multi-project management in the construction industry is its interaction patterns between different parties in project supply network as presented in Figure 1.2.

Moreover, uncertainty in construction projects raises the complexity of this kind of projects.

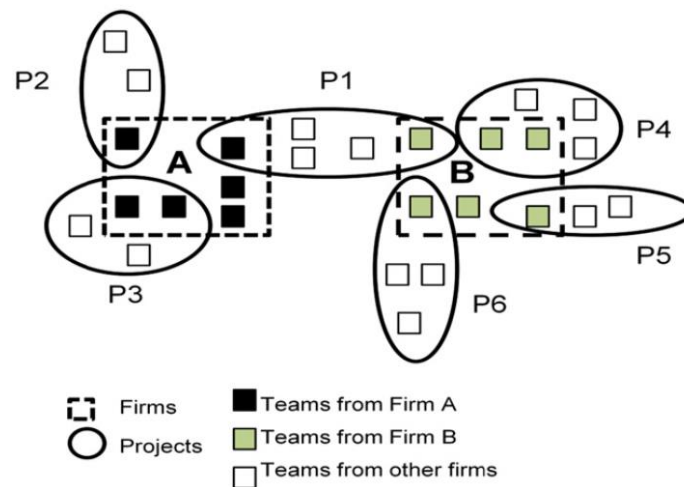


Figure 1.2 Interaction patterns in construction (Gadde & Dubois, 2010)

The researcher should find the ways to simplify the problems and reduce the conflicts between counterpart parties across the construction supply chain as well as assessing and controlling the uncertainties. Finally, supply chain design and configuration is essential for construction multi-project firms and it needs to study regarding reduction of complexity.

1.3 Area of research in project management

Project management research is widely distributed in different categories (Winter et al., 2006). Some of them focus on project planning and scheduling by referring to the critical path method (Davis, 1966). In this line of study, resources are allocated to the network's activities and start and finish time of each activities are determined (Demeulemeester & Herroelen, 2002). This strand of study has been criticized by some scholars and practitioners for a number of reasons. It does not pay attention to the emergent nature of front-end work, it tends to treat all project environments as the same, and finally does not sufficiently account for human issues (Winter et al., 2006). So the attention of the other parts of studies that emerged in the late 1970s goes to organisational issues such as its structure design as a means of achieving integration and task accomplishment, organisational alternatives from functional through matrix to project. The more recent third strand of research that has been started in the late 1980s and still plays an important role in the research area and brings a huge amount of contribution has looked at major projects in specific sectors and emphasises the

context and front-end work (Winter et al., 2006). In this line of research, focuses are on inter-firms relationships, contract, and negotiation criteria between supply chain partners, analysing performance efficiency etc. (Söderlund, 2004).

One could easily realise “the need for an interdisciplinary approach to conceptualization and theorising of project management practice, and careful consideration of the methodological issues by researchers in order to enable to creation of knowledge perceived as useful by practising managers” (Winter et al., 2006).

1.4 Statement of the problem

In this research, a genuine project portfolio management problem particularly for the construction industry (CI) will be studied. It means that in a real situation most of the main contractor construction companies work as multi-project firms. They are involved with complex projects, in a dynamic, uncertain, risky and competitive environment. Clients ask for bids from the portfolio/business managers, portfolio managers allocate a qualified and expert project manager to each project. Project managers should find the best collection of different traders/subcontractors in order to achieve the business objectives. In this case, having an experienced and expert project manager who could use lessons learned from the past projects is a vital issue for the company to achieve future objectives. So, expert project managers are usually well rewarded. Where selecting and coordinating between different subcontractors is the main challenge of the project managers, each project manager competes and in some extent collaborates with others to obtain qualified resources (subcontractors) for its own project. These resources are autonomous and independent with regards to their decisions within the supply chain of the company. Therefore, interaction and interconnection among different parts of the supply network is essential. The problem is how portfolio management could select the projects, how it could select the best combination of the subcontractors and different required trades of the projects, and how they could integrate these decisions with the decisions regarding project planning, scheduling and rescheduling if required. The portfolio management team need to be able to answer questions such as: What is the effect of entering a new project or finishing

a project on the portfolio and the enterprise supply chain? How could risk be assessed in project selection and also subcontractor selection and control in order to increase the enterprise's performance? How could the portfolio manager configure resources across the business supply network to deal with uncertainties? What is the relation of the aforementioned decisions/questions with the company's success and reputation?

These questions lead to the objectives of the present research that are described in the next section.

1.5 Objectives

The purposes of the research are as follows:

- To investigate the existing methodologies in hierarchical multi-project management and the available models in each level of the hierarchy i.e. project scheduling (operational level), project selection (tactical level) and supply chain configuration (strategic level), in general and specifically in the construction industry.
- To identify the relationships and interactions between different parties who interact in project portfolio management in the construction industry organisations, and to identify the modelling and technical requirements for constructing an applicable framework for hierarchical multi-project planning and control in the construction industry by conducting case studies.
- To investigate the ways of integration between different levels of decision making including bidding processes, subcontractor selection and project planning in order to move from traditional contractual approaches to the supply chain and partnership agreements.
- To construct a framework and establish the required methods and procedures for practical hierarchical construction multi-project management in order to integrate strategic, tactical and operational decisions. These methods must be able to integrate different levels of the hierarchical framework, from the operational level by project planning and subcontractor assignments, to the tactical level by bidding preparation and client

negotiations and finally at the strategic level by supply chain configuration based on lessons learned, and organisational learning theories.

- To validate the feasibility of the proposed approach using a prototype Multi Agent System- Decision Support System (MAS-DSS) which was partially implemented (please see Figure 6.1) and by interviews with experts at the case study companies.

1.6 Research Methodology

Considering Winter et al.'s (2006) suggestions for future research directions in project management in the UK, they emphasised conducting research that is useful for practitioners and call for the use of methodological theories. In addition, research efforts in the field of hierarchical multi-project management showed that in order to establish a framework for real world multi-project planning and control, understanding the business and industry environment plays a crucial role (Hans et al., 2007). The construction industry was selected for this study. A detailed literature review in general and in construction industry, in particular, was conducted at different levels of Hans et al.'s (2007) hierarchical framework (i.e., operational, tactical and strategic levels). A review of the bulk of literature gave evidence to the fact that in construction industry subcontractor selection, client negotiation and bid preparation are among the major elements of the business processes.

So, beside the academic literature review, an in-depth case study was conducted in which close relationships with practitioners provides insights to propose a new solution that enables enterprises to manage the complex project portfolio and supply chain operations that are characteristics of the construction industry (CI).

The case study focused on understanding the relationships between the general contractor and subcontractors and also between the general contractor and the client for each individual project in the portfolio. It showed that organisational development theories such as organisational learning (Tennant & Fernie, 2013) and inter organisational partnership (French & Bell, 1990) are relevant theories, particularly where the temporary nature of the project organisation (Thomas &

Mengel, 2008) and geographically distributed construction projects (Xue et al., 2012) make it more complex than other businesses.

The literature review in hierarchical multi-project planning discovered the existing gap in the first year of the research schedule. In the second year of the research, an in-depth case study was conducted which provided insightful information. By combining the available theories and the perceived knowledge from case study, an integrated hierarchical framework for multi-project management in construction industry was constructed. The framework and its procedures were prototyped in the form of a multi agent system - decision support system MAS-DSS in order to support decision making in complex, distributed business environment.

The prototype MAS-DSS was presented to the case study's practitioners at the end of the second year of the research time window. The feedback was received from different angles, analysed and the model revised. Although the holistic framework was agreed by the practitioners, more literature review was conducted to deal with its shortcomings particularly in relation to uncertainties and key performance indicators in the construction environment to improve the coherence of the framework and its procedures. This process took over 6 months. Then the revised version of the framework was presented to the other case study companies to examine the correctness, usefulness, applicability and practicality of the proposed framework and its procedures at the end of the third year.

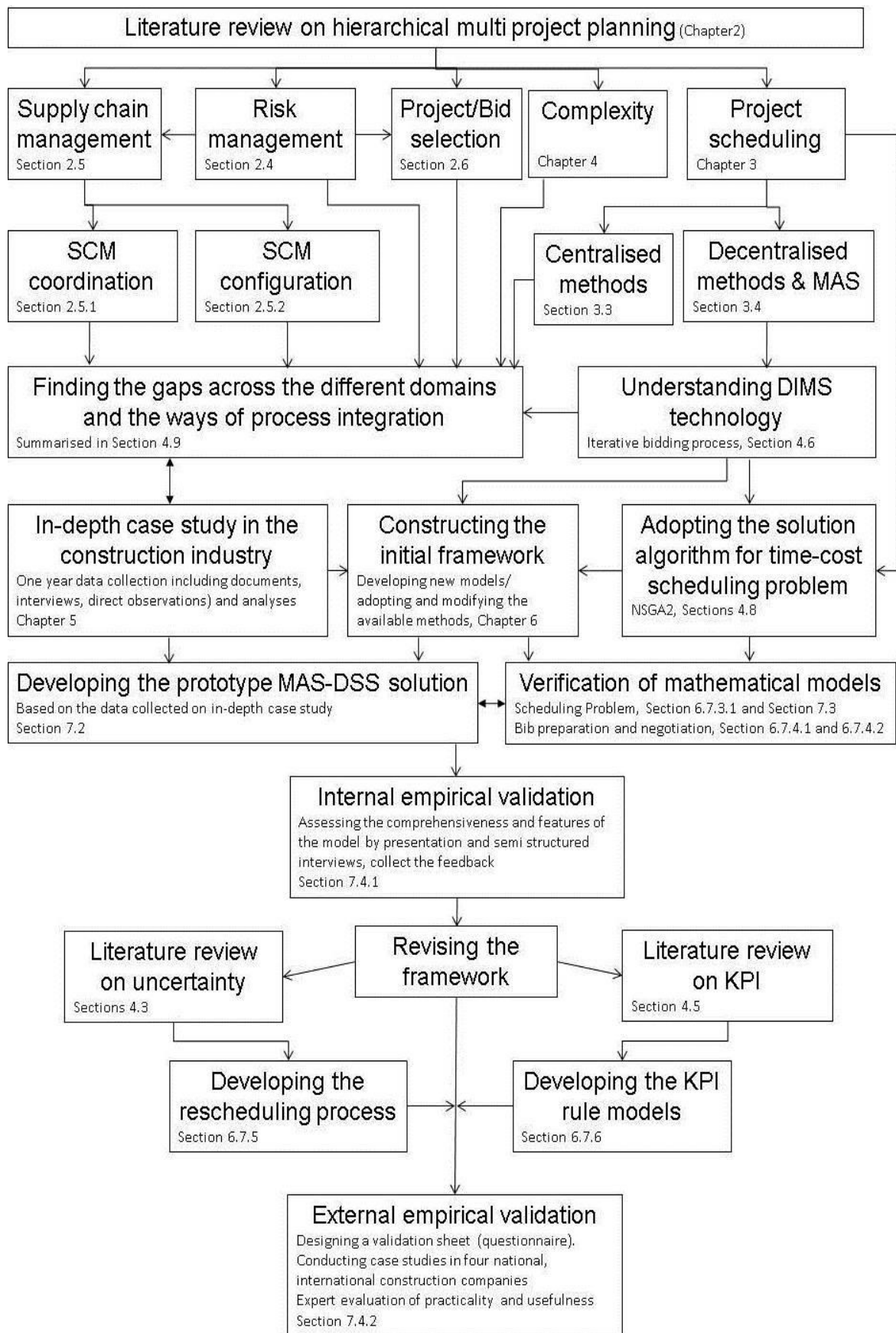


Figure 1.4 and Figure 1.3 present the actual research schedule and the utilised

research method.

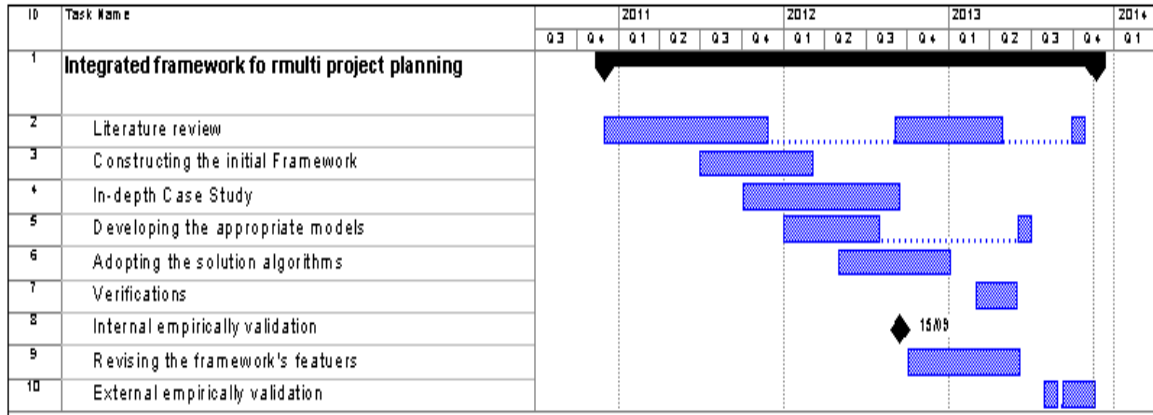


Figure 1.3 The actual research schedule

The details of the research methodology outlined in

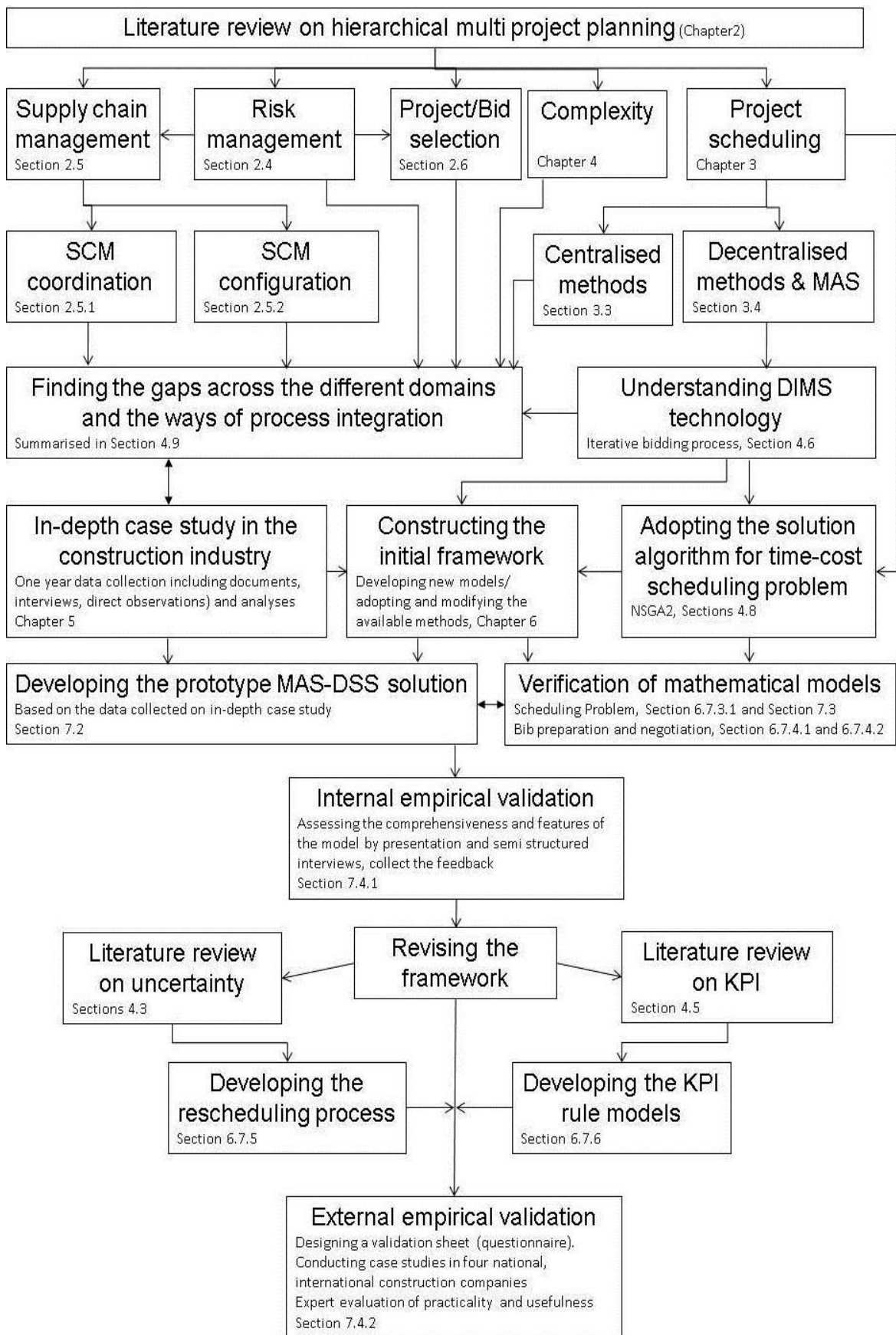


Figure 1.4 are explained in the following subsections.

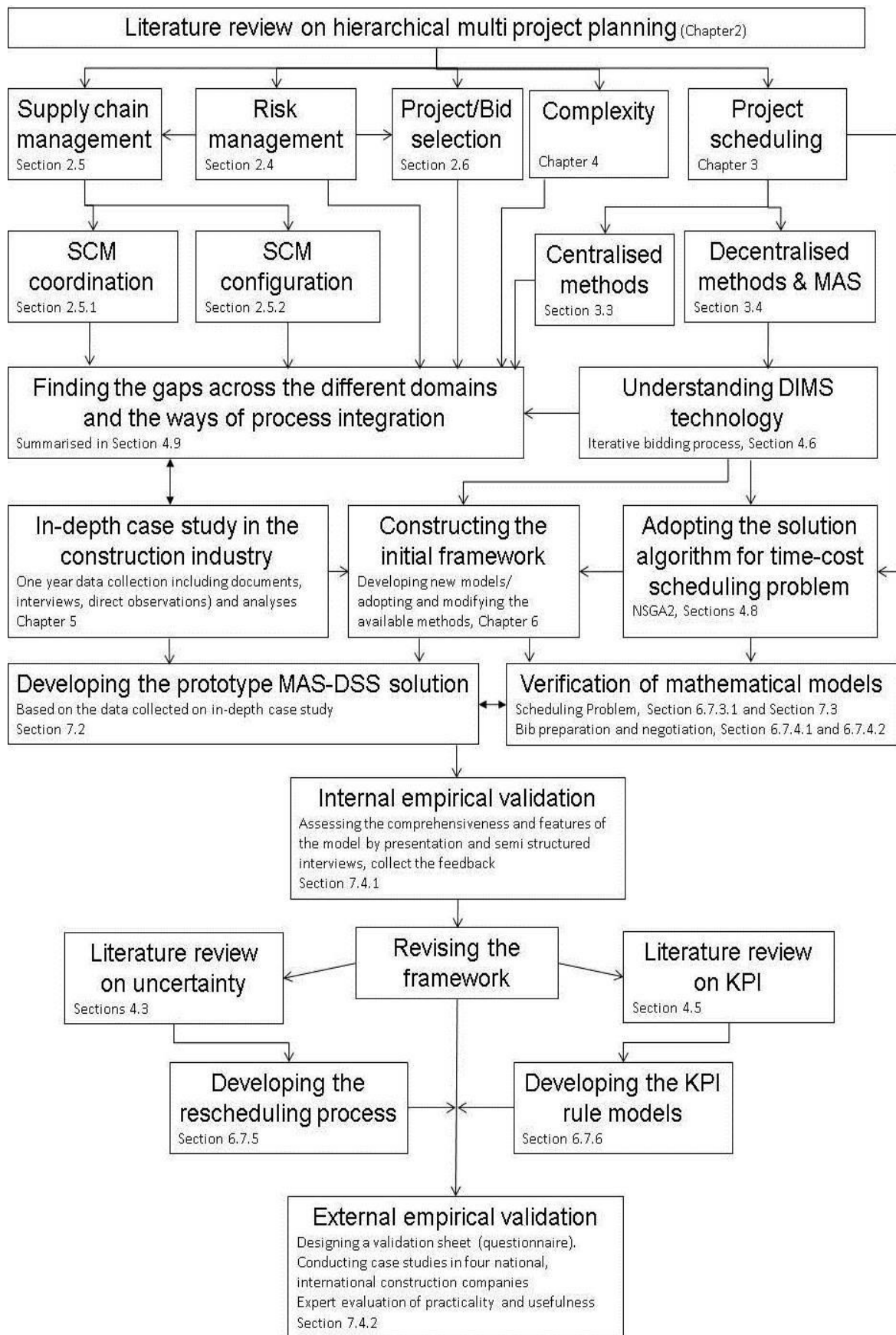


Figure 1.4 The overall research method

1.6.1 Literature review

First the varieties of models and algorithms for dealing with hierarchical project portfolio management were reviewed. The review covered supply chain management, risk management, project/ bid selection as well as multi-project scheduling problems. The review was conducted in order to investigate the current knowledge and to identify the areas of research and directions of the future studies in the field of project portfolio management. Multi agent systems (MAS) were also investigated as a novel methodology for dealing with complex distributed multi-project management. Moreover, ‘dynamically integrated manufacturing systems’ (DIMS) (Zhang et al., 2007), a state of the art technology for manufacturing systems, was studied to understand how it could be adapted for managing the project portfolios. The literature review process is presented in Figure 1.5.

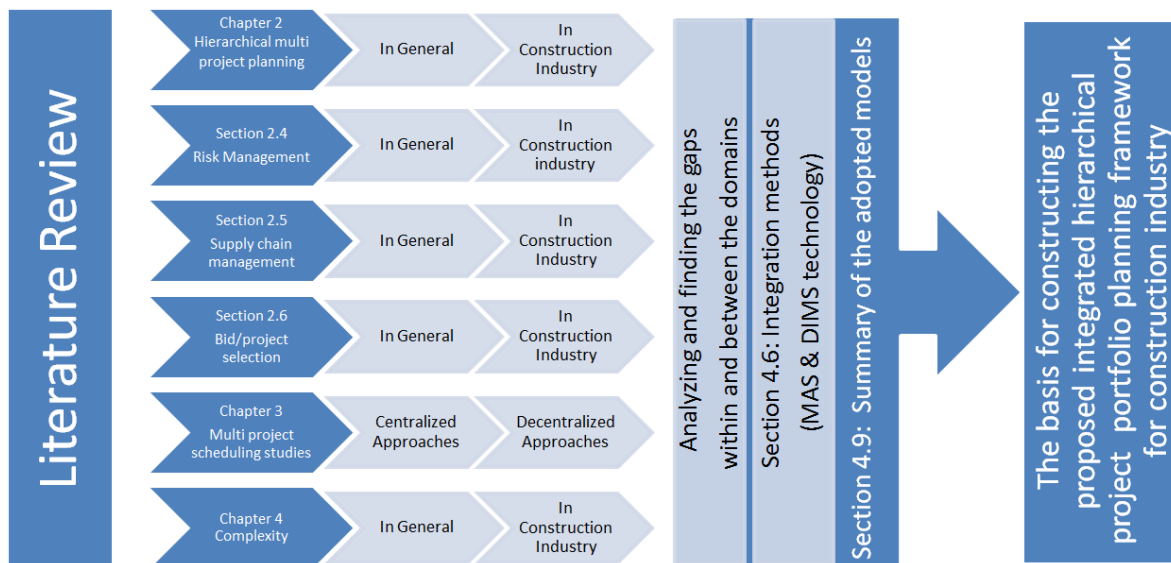


Figure 1.5 The literature review process

The aim of the literature review was to find the gaps existing in each domain in order to construct the new algorithms or adopt the most appropriate models for this study and also to find ways of combining developed or adopted models to put them into an integrated framework.

1.6.2 In-depth Case study

In line with Winter et al. 's (2006) suggestion, this study attempted to close the gap between theory and practice. Having identified the main gaps in the literature review, it became clear that organisational learning and information technology are

two main streams (Robey et al., 2000) that can accommodate the complexity of decision making processes in hierarchical distributed multi-project management.

Therefore, in order to understand how practitioners work and the problems they face, conducting the case study was a promising methodology that was selected (Voss et al., 2002) and (Barratt et al., 2011). As Voss et al. (2002) argue, a case study is one of the most appropriate methodologies adopted by researchers and practitioners for generating and/or testing a theory. Particularly, in organisational development theory, an in-depth case study has been accepted as a commonly used methodology (French & Bell, 1990). The method used in this research is an in-depth case study very similar to action research where the learning process took place in the field and initial proposed framework has been evaluated in the first company.

The in-depth case study that lasted for over 11 months at University Partnership Programme (UPP), focused on understanding the organisation as a whole with respect to project portfolio planning processes. In this case, project selection, subcontractor selection, and negotiation between different actors including clients, portfolio manager, project managers and subcontractors were all investigated to find out how they interact with each other to come up with the contract agreement, project scheduling and rescheduling, and how they identify the risks associated with the projects. What sort of information system they use, how knowledge and skills of expert who work in a particular site might be shared within entire enterprise and can be utilised for resource management across the multi-project enterprise that work in different geographical locations such as Exeter, Reading and Nottingham.

Regarding the data collection, 'Documents, archival records, interviews, direct observation, participant observation, and physical artefacts' are the sources that can be used as evidence in case study (Yin, 2008). In a similar vein, the author collected the data from the first case study company and its projects from a number of sources including, contracts, periodic progress reports, subcontractor database, direct observation, taking photos and videos from progress of the project along with informal discussions with different people who worked in the

organisation such as site managers, project manager, portfolio manager and admin staff. In addition, informal interviews were conducted with two of the subcontractors and also the contract manager of the client.

Semi-structured interviews were also utilised to evaluate the proposed model. This will be discussed later.

The above-mentioned processes took nearly one year. It started at early stages of the project in October 2011 and lasted until handing over and project finishing process on 15/09/12.

1.6.3 Constructing the integrated framework and its required procedures

The hierarchical integrated framework that had been initially constructed at the first year of the study was the basis for developing the required tool for “managing the complex project portfolio and supply chain operation” system design. The initial model was designed based on multi-project resource constrained models. However, the real world constraints and limitations identified through in-depth case study supported the improvements of the framework in later stages. The information collected from the case study was analysed and interpreted and finally perceived knowledge compared with the literature in order to construct the new model of inter organisational collaboration and supply chain management of the project and the enterprise supply chain.

The decision making process in multi-project planning in main contractor companies was shown to be more complex than traditional models in construction project scheduling (Zhou et al., 2013) could accommodate. So, decision making in bid selection, subcontractor selection and project planning were incorporated and integrated together to combat the pitfalls of current available models in multi-project planning. This provided a new method for dealing with subcontractor selection in construction industry that in turn facilitates negotiations between portfolio manager and client. An adaptive approach was adopted to dynamically integrate these decision makings territories.

1.6.4 Validation and feedback from the first case study

In order to validate the integrated framework for hierarchical multi-project planning in construction industry the use of human expertise was adopted. This approach is the most popular used methods and the best practice (Chapurlat & Braesch, 2008).

As Chapurlat & Braesch (2008) explained, this approach of validation of the framework “consist in discussing and appraising the model within the framework of reviews, meetings or by using certain simple tools like the automatic generation of documentation starting from the model. So, after modelling the system, human expert can check the model., the knowledge and the know-how of an expert or a group of experts can interpret this model or interpret results resulting from its simulation, and draw a certain amount of additional information from it.”

In this research, a prototype MAS-DSS model that encompasses the most important features of the proposed model was developed to be presented to the experts. The prototyping approach to information systems has been used in project management information system studies by scholars as discussed in (Ahlemann, 2009).

The prototype MAS-DSS software was partially developed on the basis of rapid application development (RAD) methodology in which the emphasis is on end-user engagement and client perception rather than documentation (Martin, 1990). The reason for developing the prototype MAS-DSS was that the experts involved in the case studies did not have relevant knowledge and experience of using modelling languages such as UML, IDEF, etc., so these models were not relevant for evaluation of the proposed model. In addition, it was a more promising approach that could facilitate communication and dialogue between the researcher and experts who had many years' experience in construction industry but lack of knowledge in formalised enterprise modelling as discussed in Chapurlat & Braesch (2008) and Ni et al. (2007) .

Therefore, by means of the prototype tool, the new approach was presented to the first case study management team including director and two of the project managers along with the client's contract manager in a presentation meeting followed by open-ended questions. The MAS-DSS presentation caught the

attention of the experts for discussing the features and model characteristics. The experts all welcomed the new approach and some insightful ideas were shared based on the open-ended interview followed by the system presentation. The presentation and interview were recorded, transcribed and analysed. The feedback, particularly in dealing with uncertainty that exert influence on rescheduling decisions was considered for revising the first generation of the proposed prototype MAS-DSS.

1.6.5 Adopting solution algorithm, testing the model and verification of proposed solution

When the proposed framework was agreed by the experts, the next step was finding the exact solution for the part of the framework that is concerned with optimization. NSGA2 (Deb et al., 2002) was adopted to solve the problem and to obtain the results for some instances of the collected data. The results showed that the solution that was currently used in the company was one of the solutions obtained from multi objective genetic algorithm; however, the proposed approach improved the negotiability of the contract process.

1.6.6 Improving the framework

The insightful feedback gained from the case study validation process shed light on improving the framework in order to enable the model to address more relevant and vital feature to the system. Particularly, the feedback in relation to uncertainty and risk management associated with supply chain and subcontractor selection were taken into consideration along with conducting comprehensive literature review in these areas. These helped to improve the models and to adopt the required procedures within the framework and made it more useful for addressing the real world construction environment.

1.6.7 External Validation

The revised framework fulfilled the practitioners' requirements in the first case study company. However, in order to understand how this model could be utilised by other construction organisations an external validation step was adopted. External validation can potentially increase the rigour of the study and resolve the potential bias (Barratt et al., 2011).

To do so, the improved framework has been validated through several meeting presentations for both national and international companies. Using the revised prototype MAS-DSS system in the presentation meetings helps the practitioners to understand the entire system in a practical and tangible way rather than asking them to read extensive explanation documents such as IDEF models Chapurlat & Braesch (2008). This was one of the benefits of rapid prototype software design notion (Martin, 1990) which enabled very busy practitioners (project managers and portfolio managers) to participate in this research.

The framework received the appropriate acceptance from the practitioners although some of the limitations were revealed for further research. This can be referred to generalization concepts argued by Walsham (1995) in Information System (IS) research methodology. Therefore, in line with Winter et al.'s (2006) guidelines, the outcomes of this research could be suitable for construction environment where the practitioners could easily use the proposed frameworks and its associated MAS-DSS.

1.7 Structure of the thesis

In the following chapters, first the varieties of frameworks, models and algorithms for dealing with hierarchical project management are discussed. Hierarchical multi-project planning and control will be explained in Chapter 2. The different decision levels of this hierarchy will be discussed in the same chapter where first supply chain management will be discussed and then project selection will be reviewed. Since multi-project scheduling plays the crucial role in hierarchical multi-project planning, Chapter 3 is devoted to this matter. The chapter begins with the definitions and characteristics of the single project scheduling. It will be continued to the centralised multi-project scheduling problem. For both cases the exact, heuristic, and meta-heuristic models with more interesting objective functions, which scholars concentrated on for the last half a century will be reviewed. Then, decentralised multi-project scheduling, using multi agent systems will be reviewed. Among those, the one that considers two layers of hierarchical project planning will be highlighted in a separate section.

The dynamic and uncertain characteristics of multi-project management are illustrated in Chapter 4 where a complex adaptive framework that has addressed these features will be reviewed. Finally, as a candidate methodology, DIMS - Dynamically Integrated Manufacturing System - which was developed in XMEC (Exeter Manufacturing Enterprise Centre) for manufacturing systems will be investigated to identify the lessons that might be learned from the manufacturing systems research stream.

These are critically analysed to find out the available existing mechanisms for integration between operational, tactical and strategic decision making levels as well as their short-comings in the view point of applicability in construction industry.

Chapter 5 is devoted to introducing the case studies conducted in market leader construction companies. First it focused on one of the active sites at the time of conducting the present research at the University of Exeter. Second a number of case studies in other market leader companies are introduced in this chapter.

The literature review and case studies shed light upon the idea of process integration by the use of multi agent systems. This helps to improve the business processes. So dynamic hierarchical integrated project portfolio management framework by the help of multi agent architecture was proposed and presented in Chapter 6. This framework and methodology can enable the management to accommodate the complexity that emerged from uncertainty and risk in the multi-project construction environment where different actors/agents interact to achieve their individual objectives. The integration of operational, tactical, and strategic decisions in this framework in the construction industry is also illustrated in this chapter. The novel method for integrating bid/project selection, bid processing and negotiating, subcontractor selection and project scheduling will be described as well. Then the proposed feedback learning method that enables the enterprise to reduce the uncertainty existing across the business network will be illustrated to explain how it could help to move from a traditional contractual bidding process to the supply chain configuration and partnership agreements in strategic layer of the framework. Since the proposed methodology was based on real case study

observations, uncertainty and risk analysis were captured in a practical way that could be utilised by the practitioners as well.

Chapter 7 demonstrates the partial implementation of the framework in a MAS-DSS software package and the verification process that used by the prototype (non-commercialised) MAS-DSS software. The verification of the proposed model is also illustrated in the same chapter.

Chapter 8 is devoted to the summary along with a discussion about the contribution of the present study. The discussion highlights how the proposed framework can close the gap between theory and practice. The limitations of the study, the conclusion and further research works are also addressed in Chapter 8.

CHAPTER 2 HIERARCHICAL MULTI-PROJECT MANAGEMENT

2.1 Introduction

In multi project based organisations, management teams are dealing with highly complex decisions related to project selection, resource scheduling and supply chain development. Since the status of the projects is continuously changing, the resource structures dynamically change over time. Thus, multi-project organisations are distinguished by a high level of complexity and uncertainty regarding the activities and operations. The coordination between different parts of this kind of organisations is very complicated. Portfolio management needs decisions such as project selection, bid preparation and negotiation, and project planning and control.

According to the devised research methodology discussed in Chapter 1, in this chapter, the research works in the field of hierarchical multi project planning are reviewed. First, the basic characteristics of project planning are introduced in Section 2.2. In Section 2.3, hierarchical multi-project planning in general and particularly in the construction industry is discussed. Based on the literature, there are three main levels of decision making processes in the hierarchy. They are strategic decisions that are related to the supply chain configuration, tactical decisions that are related to project selection and bid preparation and finally operational decisions such as subcontractor selection and also project scheduling/rescheduling decisions in project levels. In order to construct an integrated framework, these features need to be understood and the existing gaps need to be analysed. Therefore, in the next three sections (2.4 - 2.6), project risk management, supply chain management and project selection, will be reviewed and the available models in each domain are evaluated for their suitability for a hierarchical multi project planning framework and to identify the gaps remaining for further work. Moreover, the relations between these interrelated domains are identified to seek how these decision processes can be integrated to shape a

hierarchical multi-project planning framework. Finally, in Section 2.7, a summary of the chapter is provided.

2.2 Basic characteristics of project planning and scheduling

Before commencing the literature review in project planning in this section the basic characteristics of the problem are illustrated to provide a common ground for further discussions. From the project planning point of view, the problem is classified according to the types of activities, type of resources, objective functions, and type of the decision-makers. Briefly, each of which are described as follows:

2.2.1 Activity and network characteristics

A project is comprised of several events and tasks that have to be performed based on a set of precedence constraints. A 'network of activities' or 'project network' shows the necessary interdependencies of the activities. It could be presented in two ways, activity-on-arc or activity-on-node. The project network is supposed to be topologically sorted, i.e. each predecessor of activity j has a smaller number than j . In addition, activities $j=1$ and $j=N$ are unique dummy source and sink respectively.

In addition, there are several types of precedence relationships between activities such as finish-start, start-start, start-finish, and finish-finish each of which could define with minimal or maximal or combinatorial time-lags (Demeulemeester & Herroelen, 2002). Moreover, the duration of each activity and time-lag could be deterministic, stochastic or fuzzy. Finally, in the case of multi-project management there are two types of networks including super-network and Multi-individual-network.

2.2.2 Resource types

Resources are necessary for conducting activities. As commercial activities depend on limited resources, resource constrained project scheduling problem (RCPSPP) is a very important strand of study. The Type of resources in RCPSPP are categorised as renewable, non-renewable, partially renewable or doubly-constrained.

Renewable means that a pre-determined number of units of a resource is available for each specific period of planning horizon like manpower, machines, tools, etc., while non-renewable expresses that a number of units of a resource are available for the entire planning horizon. It seems that money could be one of the best examples of non-renewable resources when the total amount of it is limited to a certain budget for the whole project. Partially renewable resources as well as dedicated resources that can be assigned to only one activity at a time are the other type of resources that one could find in the literature (Demeulemeester & Herroelen, 2002).

2.2.3 Project scheduling objectives

A variety of objectives could be found in literature, which are all derived from the real world. They are generally categorised as time-based objectives, resource-based objectives, financial-based objectives, quality-based objectives, robustness-based objectives, reactivity-based objectives, and finally multiple objectives and multi-criteria approach in order to reach Pareto-optimal solutions. e.g. time-cost trade-off , time-resource trade-off and more recently time-cost-quality problems. For more detailed and comprehensive description of each above-mentioned characteristic one could see (Demeulemeester & Herroelen, 2002).

2.3 Hierarchical multi-project planning

By reviewing the literature, it is understood that the term 'multi-project planning' has been applied for different layers of decision making based on planning horizons which divide into the Strategy Planning (long term planning), Tactical Planning (medium term planning) and Operational Planning (short term planning). There are research works which have considered a single-level managerial mechanism for multi-project planning. In this case, a single manager supervises all projects in different planning horizons (i.e. short term, medium term and long term).However, there is a consensus that a hierarchical decomposition is needed to achieve a more manageable planning process and to overcome the complexity of the problem. The literature has provided extensive analyses of the hierarchical

multi-project planning over the years (Speranza & Vercellis (1993), Shankar & Nagi (1996), Neumann et al. (2003), Hans et al. (2007), Can & Ulusoy (2010)).

The dual-level managerial structure mechanism is one of the common methodologies employed for managing multiple projects. Yang & Sum (1993) suggest a dual-level structure which comprises a top manager or resource pool director and a number of project managers. In this structure, project managers work at an operational level and are responsible for scheduling the activities of individual projects. The top manager works on a tactical level and is responsible for all projects and project managers. At the top level, projects are scheduled as individual entities in order to determine start times and due dates for each project. In addition, the top manager allocates the limited resources to the critical projects. Then based on this framework, each single project is scheduled individually by each project manager. Shankar & Nagi (1996) also proposed a dual level mechanism comprised of two stages i) Planning and ii) Scheduling. A linear program was used for planning stage, which provides a range of selection among multiple objective functions. The second stage uses a metaheuristic method namely simulated annealing (Jeffcoat & Bulfin, 1993) to calculate the solution. This approach has been recently improved with a 2-stage decomposition algorithm presented by Can & Ulusoy (2010) for the multi-project multi-mode problem, based on the concepts of macro-activity and macro-mode, which were initially introduced by Speranza & Vercellis (1993).

Neumann et al. (2003) demonstrated a three-level hierarchical multi-project planning process. They considered a portfolio of long-term projects within a planning horizon of 2–5 years. For each project, the release date, deadline and work breakdown structure are given. They considered three types of renewable resources as follows:

“(a) Strategic key resources like experts, research equipment, or special-purpose facilities. The procurement of key resources often belongs to the general business strategy and may require several years of lead time.” They assumed the availability of those resources to be given.

“(b) Expensive primary resources such as technical and administrative staff or machinery, which can be procured from the market for the medium term.

These resources are usually not considered in the context of long-term planning.

“(c) Low-cost secondary resources, e.g. tools or auxiliary devices, which similarly to primary resources, can be supplied in adequate amounts for the medium term. Secondary resources are disregarded during long and medium-term planning. For short-term planning, however, their availability must be taken into account” (Neumann et al., 2003).

A summary of the hierarchical planning approach by Neumann et al. (2003) is shown in **Error! Reference source not found.**

Table 2.1 Hierarchical multi-project planning (Neumann et al., 2003)

	Long-term	Medium-term	Short-term
Planning objective	Project Portfolio	Condensed project	Detailed project
Aggregate activities	Subprojects	Working packages	Individual activities
Resource types	Key resources	Key and primary resources	Key, primary and secondary resources
Objective function	Maximisation NPV	Resource levelling	Minimising Makespan

At the first level (long term) all the projects are grouped into a super-network. The release date and deadlines are modelled using generalised precedence relations. The aggregate activities are to be scheduled subject to scarce key resources. The estimated duration of an aggregate activity equals the critical-path length of the corresponding subproject plus a time buffer that anticipates the time extension of the aggregate activity that will occur due to the scheduling of the disaggregated projects at the third planning level. By employing queuing theory, they estimate the size of the required time buffers.

The key resource requirement of an aggregate activity is calculated as the ratio of the total workload of the related subproject and its pre-estimated duration. They assume that the capacity of the key resources is given by the general business strategy. Firstly, at the highest level of the hierarchical planning, maximisation of the net present value of the project portfolio is the objective function. The resulting schedule provides a minimum duration for every project, and the resulting resource

profiles provide the time-dependent resource capacities for the key resources at the second planning level. Then, at the second level (medium term), primary resources with unlimited availability has been considered. Each project is reduced by choosing the aggregate activities to be the work packages. The durations, time lags and resource requirements are determined similar to that at the first level. At the second level, the objective is to level the use of these resources over the project duration. Finally, at the third planning level (short term) the condensed projects are disaggregated into detailed projects with individual activities. Resource constraints are given for the key and primary resources as well as for low-cost secondary resources. The objective is to minimise the project duration.

Since in this model projects are grouped into a super-network at the beginning of the planning horizon, it is a static model and is not suitable for dynamic real multi-project firms.

Hans et al. (2007) proposed a hierarchical multi-project planning and control framework, which helps classify different aspects of managerial decisions in multi-project organisations as shown in Figure 2.1.

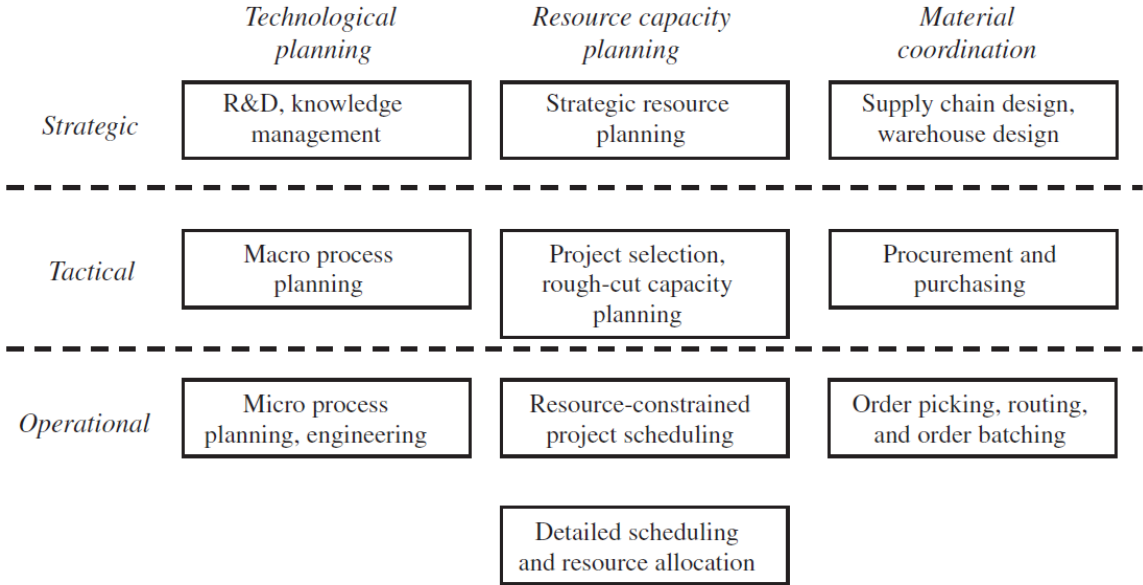


Figure 2.1 Hierarchical multi-project planning and control framework (Hans et al., 2007)

Their proposed framework comprises three hierarchical planning levels including Strategic, Tactical, and Operational levels. The novelty of their framework is that, they not only have considered three hierarchical levels for “resource capacity planning” domain including i) Strategic resource planning, ii) Project selection and

rough cut capacity planning, iii) Resource-constrained project scheduling aggregated with detailed scheduling and resource allocation, but also supply chain design and warehouse design have been included in their suggested framework at the functional planning area of “Material coordination”.

Project selection has been located at the tactical level of this framework. In addition, at the tactical planning level, managers are faced with essential decisions such as allocating resources between unlike projects and ascertaining due dates for tendering purposes which are called rough-cut capacity planning (RCCP). The time horizon over which this planning analysis is undertaken tends to be generally medium to long, and is only derived from an aggregate level of knowledge of the various activities comprising the set of projects. It is noticeable that such decisions have an immense effect over the entire productivity performance of a business, and that they can even affect its competitive strength, by determining the cash-flow profiles (as Vercellis (1994)) and the delivery dates designated for bidding proposals (Hans et al., 2007).

Project scheduling is located at the operational level of Hans et al.’s (2007) framework. The time horizon over which this planning analysis is undertaken is short to medium. In this level generally, the activity modes are set and the timing of the activities is determined. Seeking the optimal trade-off between the incorporation of resources, the time duration of each operation and the costs related to substitute 'modes' of executing each activity are the main objectives of this level of planning.

In addition, they have proposed a positioning framework for selecting appropriate models and methods for multi-project planning in project portfolio companies. Considering this positioning framework (which will be discussed in detail in Chapter 4, Section 4.3.2), they claimed that there cannot be a generic model for multi-project planning that would be suited for all enterprises. Thus, Hans et al. (2007) suggested that the best way to coordinate, schedule resources and control schedule performance depends on the project environment. So, each industry needs to be investigated and an appropriate method for that sector should be proposed.

According to this argument, they were unable to suggest any generic mechanism to integrate planning and scheduling in different levels of their framework for all the industries. However, as an example they referred to a PhD thesis (De Boer, 1998) as a practical case that proposed a DSS solution for the Royal Netherlands Navy Dockyard (RNND), a public company that is responsible for the maintenance, repair and modification of national defence marine equipment. De Boer et al. (1997) described the implementation of a hierarchical DSS for multi-project planning at RNND. The proposed DSS includes tactical and operational levels in a hierarchy. In the tactical level, deterministic rough cut capacity planning is used to determine resource allocation and due dates for each arrival project. In the operational level, a deterministic resource constrained scheduling problem for each project (RCPSp, see Section 3.2) that aims to minimise the makespan of the arrived project is utilised to determine the scheduling of each particular project. Although the DSS is used in industry, there is no attention to uncertainty existing in the enterprise where rescheduling may need to be conducted. Therefore, Hans et al. (2007) finally argued that regarding the recent proposed planning techniques which covers uncertainty (see Section 4.3) this DSS needs to be improved and updated.

Moreover, although Hans et al. (2007) discussed interaction between hierarchical levels of capacity planning function in their framework, the interconnections among different domains of their proposed framework i.e. technological planning and material coordination (particularly related to supply chain management) remain unclear.

As will be explained in Chapter 5, in conformity with Hans et al.'s (2007) argument, for this research a well-known construction company who deliver quality student accommodation for the UK's universities was chosen to help understand the requirements of constructing and developing a hierarchical framework for planning project portfolio in construction industry. This allowed understanding the business environment, dependency and interdependency between several actors and the type of uncertainties that there are in front of the business to be understood. It also allowed the selection of which approaches and methods were more fitted to this

business environment. Finally it allowed the proposal of a framework and its appropriate tools and methods to facilitate decision making in a holistic manner. Since the targeted business environment was chosen to be the construction industry, in the next section the use of hierarchical project portfolio planning in construction industry will be discussed.

2.3.1 Hierarchical construction multi-project planning

Several authors have studied multi-project planning in the construction industry. Bresnen & Haslam (1991) conducted a survey including 138 construction clients drawn from both public and private sectors and found that many of the decisions are strongly affected by client experience, the strategic decisions are often internally driven by portfolio managers rather than project managers and also most of the companies prefer to work based on traditional contractual arrangements rather than other approaches. They realised that the decisions are often originated by project construction clients and there is a top-down approach rather than bottom up.

By reviewing the main literature on projects, programmes and portfolios, Aritua et al. (2009) proposed a systems model in the construction multi-project environment as shown in Figure 2.2.

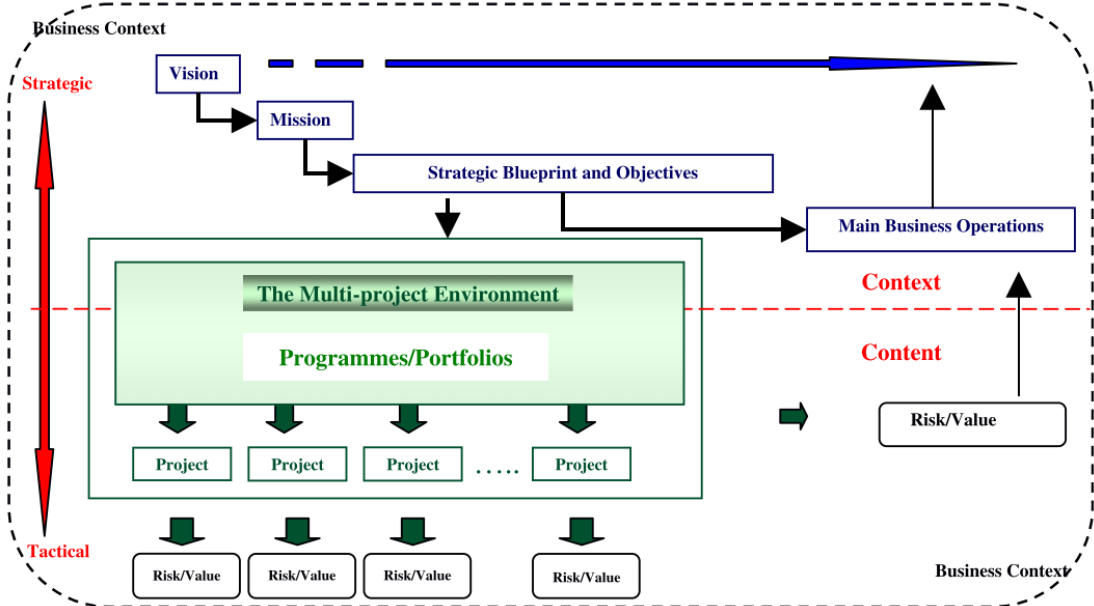


Figure 2.2 A systems model of the multi-project environment. (Aritua et al., 2009)

In this model the strategic and tactical level of hierarchy take into consideration where “the key features of the model highlight the distinction between the overall strategic issues which shape the organisation’s business context and tactical project issues. Ideally the contextual issues provide a basis for deriving the content of each project in a way that fulfils strategic objectives” (Aritua et al., 2009). They believed that the aim of executing the multi-projects is to attain some business objective and/or hybrid business and project objective. They claimed that “the project is undertaken as part of an open system and as such is influenced by the external business climate”. Finally they argued that “Multi-project management attempts to bridge the gap between context and content and aligning projects to the overall strategy of the organisation”.

Therefore, as shown in Figure 2.2, they believed multi-project management – which in this case includes both programme and portfolio management – must deal with both strategic and tactical issues. Although they claimed that “the individual projects are focussed on managing risk and obtaining value in line with typical project objectives”, in their study, there is no evidence to link the operational decisions to the tactical and further more to strategic levels. However, they believed that the “multi-project management philosophy of managing projects as programmes and portfolios enables the organisation to manage risks and derive value in an integrated holistic manner that would not have been possible if the projects were managed as individual undertakings”. Therefore, they advocated that for integrating risk and value management in a holistic manner for a construction company, there is a need for conducting research efforts to integrate the risks and values derived from each single project into the portfolio and business enterprise to facilitate decision making processes in strategic and tactical levels.

2.4 Risk in project portfolio management

The origin of the risk on projects goes back to uncertainty. In this section, the author reviews risk management from both academic and practical perspectives with emphasis on construction management and the construction industry.

PMI (2013) defines project risk as: “an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives such as scope,

schedule, cost, and quality". In this definition, positive and negative risks are commonly referred to as opportunities and threats.

If a risk is identified and analysed, i.e. "known risk" management can either make a proactive plan response or, if it is not possible, assign the contingency reserve. On the other hand, for managing the "unknown risk", allocating reserves on the basis of the measured consequences of unanticipated problems on similar past projects are a promising approach.

2.4.1 Assessing and Quantifying risk in construction management

Project risk assessment and management have been hot research topics for more than ten years. Taroun (2013) conducted an extensive literature review of risk management and risk assessment covering 30 years research published in 23 journals particularly in the field of construction. He showed that in project management, quantitative risk assessment has been conducted for many years where the Probability–Impact (P–I) risk model is used to assess the risk. He argued that while conventional probability theory based approach and Monte Carlo simulation were widely used to assess the risk in other domains, due to the special nature of the projects in the case of construction industry, determining the objective probabilities and frequencies is hard to compute. Thus, project managers usually estimate the probabilities subjectively and risk assessment are often be facilitated by structuring "individual knowledge, experience, intuitive judgement and rules of thumb" (2013).

Akintoye & MacLeod (1997) conducted a survey using questionnaires to collect data. They found that the mathematical based quantitative tools for assessing risk are not acknowledged by the practitioners. Instead, experience and intuition are main tools for risk assessment. Conducting in-depth interviews based research by Wood & Ellis (2003) also provided the same results. They claimed that practitioners often trust their personal judgments and experiences and for risk assessment they often used very simple tools such as checklists and risk registers. They usually estimate the impact of risk based on cost by rule-of-thumb approaches and often add the estimated risk costs to the price of a bid as project budgeting and contingency estimation.

More recently, Laryea & Hughes (2008) conducted exploratory interviews with five UK contractors and documentary analyses. The main purpose was to understand how contractors prepare their bid prices generally and include risk costs specifically. In line with previous studies, they also realised that practitioners often use analytical tools rather than probability based and Monte Carlo Simulation methods. They found that the use of the available risk assessment tools by practitioners is quite limited. Moreover, they claimed that based on the current situation in the UK and the practitioners practices, creating more new analytical approaches is not a viable research line but providing applicable DSS software packages that developed based frequently used methodologies by practitioners could be a good solution for risk management where these methods should be examined based on theoretical approaches. They finally suggested designing risk assessment methodologies which can “appreciate the actual practice in construction industry and reflect what practitioners do in reality” in order to meet the limitations associated with the use of current tools.

Therefore, in this research aim is to select and adopt the appropriate risk assessment techniques that can be acceptable by practitioners to incorporate and combine them in the proposed integrated framework. To do so, in the next sections the literature review look at risk assessment techniques to select the appropriate methods in each topic.

The literature review highlights the important research topics in each category of the Hans et al's (2007) hierarchical framework. The aim here is to understand the existing knowledge and the gaps within each domain and also try to make a connection and establish a bridge between them to provide an integrated framework that would covers the main pitfalls of the available frameworks discussed in Section 2.3. Specifically, the next two sections of this chapter review the research works in conjunction with supply chain management and project selection as two major elements of hierarchical multi-project planning. The third element, i.e. multi-project scheduling, will be discussed in the next chapter.

2.5 Supply chain in multi-project environment

Christopher (1992) defined a supply chain as “the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer”. In the context of the multi-project firms supply chain management (SCM) is defined as “coordination of independent enterprise in order to improve the performance of the whole supply chain by considering their individual needs” (Lau et al., 2004).

Fundamentally, Artto et al. (2008) categorised supply chain relationships into two types:

- 1- Contract-based relationships based on concrete terms and conditions (rules). that is applied for a certain period of time. This type is competitive, where dependence is low and actors might frequently switch to work with the new enterprises from one project to another. Therefore, the exchange of data (price, delivery, safety etc.) is limited to the duration of the contract to make decision making possible.

- 2- “Partnership-type” relationships based on sharing risks and benefits. There are collaborative, embedded and cooperative relationships where information is openly shared. It is clear that, this type of relationship could be established based on trust, impersonal ties, joint problem solving mechanisms, and mutual commitment rather than by explicit contracts. Information is transferred openly from one partner to the other. This leads to better coordination and integration. The activities could be better monitored and therefore cost effective management could be implemented.

Particular companies can lie on a spectrum between these two extremes. Considering the characteristics of the partnership-type, it seems that for making a partnership relationship, risk sharing and trust making are two essential factors. So it could be a reasonable field of study for SCM in project based enterprises that focused on risk analysis and behavioural human action/reaction.

By conducting empirical research they showed that project based enterprises often experience both competition and co-operation between their business networks.

They called this business networks as “co-opetitive relationships, where a supply partner in one project might be a competitor in the next” (Artto et al., 2008). They also examined the business environment in project based enterprises and claimed that in this environment there are two different but inter-related networks, single project networks and business networks. They noted that between two projects it may be a gap time (see Figure 2.3) where there is no project and called it “Sleep Time”. It seems that sleep time is a very risky period for all of the actors (contractors, designers, traders, subcontractors, suppliers, etc.) who act in the business network. They should survive and pass this critical period during which they are not paid. Thus, actors who are usually entirely independent from each other become collaborators to perform their common project. However, they might become competitors as a result of the sleep time. This is one of the reasons for fragmentation in the construction supply chain.

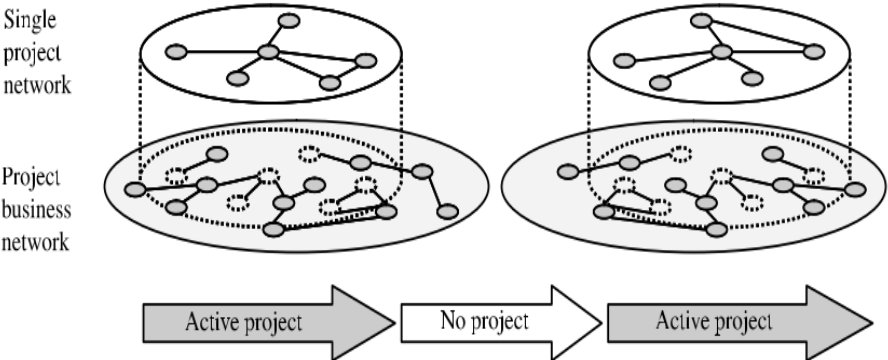


Figure 2.3 Two interrelated layers: single project network and project business network (Artto et al., 2008)

There are two categories for SCM issues:, i) coordination (execution-oriented) issues that associate with the actual execution of the supply chain and ii) configuration (design-oriented) issue that regarding the basic infrastructure on which the supply chain performs (Swaminathan & Tayur, 2003).

In the manufacturing environment, supply chain and supply chain management have been widely studied in variety of streams such as strategic, tactical, and operational subjects and covers both coordination and configuration studies. The reason might be considering this fact that the structure exchange relationship in

this environment is hierarchical, therefore activities could be completely vertically integrated by either a single company from one end to the other (from clients to the raw material suppliers) or managed by existing decentralised decision making mechanisms that have been introduced by the scholars (Li & Wang, 2007).

On the other hand, in a project environment, discrete exchanges such as co-operative subcontractor relationships and buyer-seller partnerships are often known. Thus coordination and configuration are relatively harder than Make-to-Stock (MTS) environments. Gosling & Naim (2009) conducted a comprehensive literature review of research regarding Engineering-to-Order (ETO) supply chains. It revealed that there are few publications relating to project supply chain. They provided a framework for further studies in different areas of supply chain management in ETO environment.

Considering this introduction on project supply chain management, in the next two subsections supply chain coordination and configuration will be discussed and its applications in construction industry will be reviewed.

2.5.1 Supply chain coordination (execution-oriented studies)

Hicks et al. (2000) conducted seven case study research works on ETO companies in different types of capital goods and projects such as offshore industry, oil platforms, and power station boilers. They argued that in ETO organisations, the variety of activities in projects, the tailored and complex goods and high level of uncertainties of markets, and also lack of capable and skilled resources all indicate that procurement and marketing need to be integrated with other processes such as tendering and project planning. They claimed that coordination among different parties in ETO supply chain management is essential although it is very complex.

Furthermore, within the last decade, the philosophy of SCM has been also expanded to the construction industry as project based organisations. Yeo & Ning (2002) present a process model for Engineering Procurement Construction (EPC) organisations (Figure 2.4).

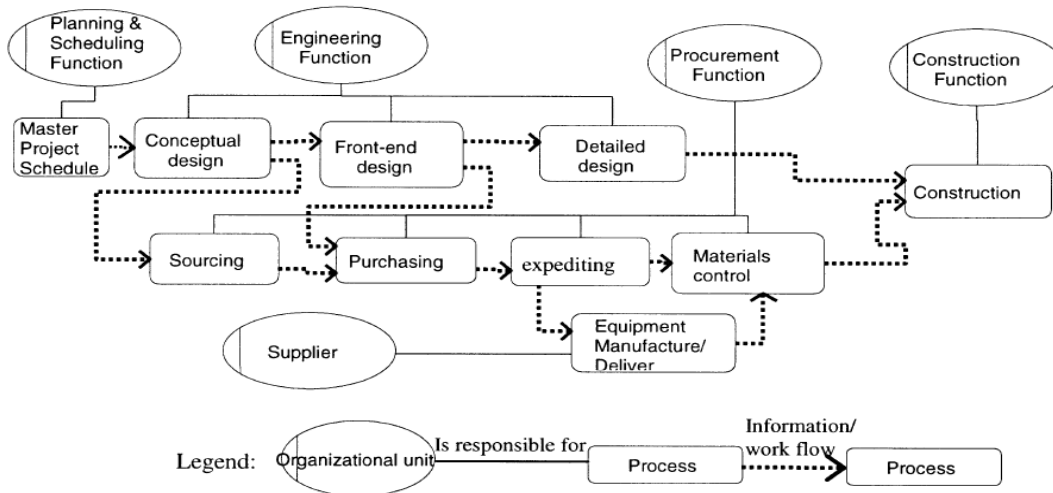


Figure 2.4 An EPC process model (Yeo & Ning, 2002)

The terminology of construction supply chain (CSC) has become popular with researchers (Vrijhoef & Koskela, 2000). Xue et al. (2005) defined CSC management as: “CSC management is the coordination of inter-organisations’ decision making in CSC and the integration of key construction business processes and key members involved in CSC including client/owner, designer, general/main contractor, subcontractors, suppliers, etc.” They provided a typical model of CSC presented in Figure 2.5.

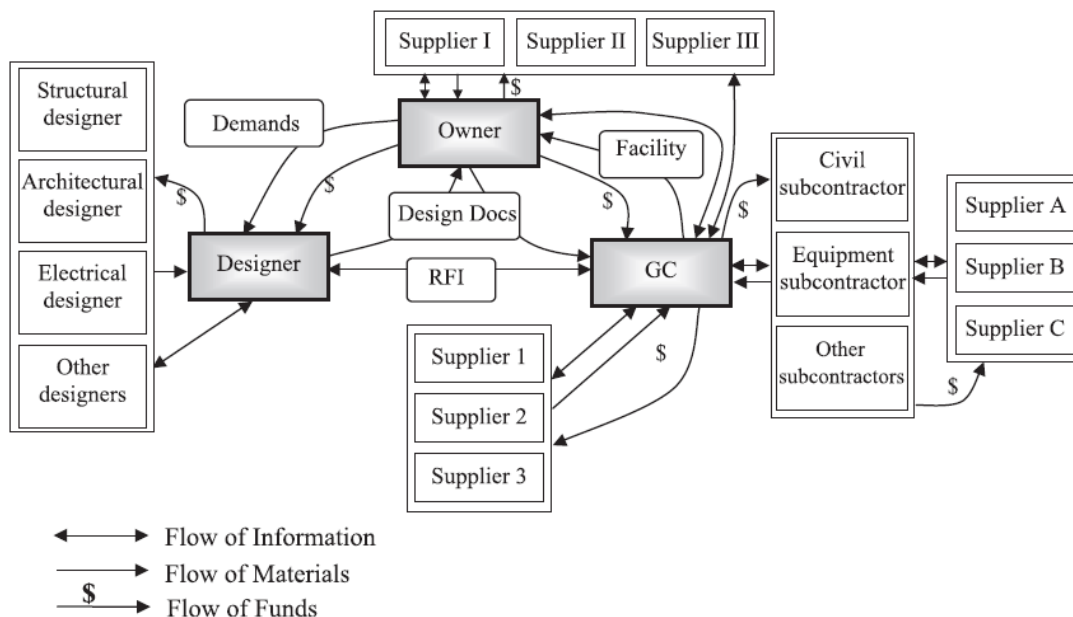


Figure 2.5 Model of construction supply chain (Xue et al., 2005)

They also recognised eight key construction business processes for CSC. These processes are “project management, client service management, supplier

relationship management, demand management, order fulfilment, construction flow management, environment management, and research and development”.

Aloini et al. (2012) argued that “SCM application has particularly found obstacles in construction sector as a consequence of its particular context of temporary multiple organization and because of the difficulties in managing networks of a large number of different companies, supplying materials, components and multiple services, and with adversarial relationships. the existing manufacturing research in SCM, although useful, cannot be directly applied to a construction environment, because of the transient nature of production in construction projects”.

However, there are a few pieces of research that investigate the state of the art methodologies to accommodate these characteristics and develop a solution for CSC developments. Since the aforementioned environment needs to be coordinated by independent individual entities, multi agent system (MAS) architecture seems to be suitable for modelling the required coordination between them (North & Charles, 2007).

For instance, Xue et al. (2005) have designed a framework based on the agent technology and multi-attribute negotiation and utility theory. A snapshot of the user interface along with the agent-based multi-attribute negotiation algorithm is shown in Figure 2.6. In this negotiation protocol, different involved parties negotiate together with respect to cost, time, quality, safety, and environment as the five main important attributes in construction industry. In each iteration, the user interface will ask the user (agent) to input its utility values to the system. The iterations will be ended when the goal (i.e. coordination) is achieved. Considering the fact that coordination sometimes is impossible, the protocol has the “no solution” option as it is seen in the figure (grey circle numbered 8).

They defined several different agents including general contractor agent, owner agent, designer agent and groundwork, civil and structure, building services, finishing works, concrete supplier, finishing material subcontractor agents and finally three service agents including agent name server (ANS agent), monitor agent and construction coordinator agent.

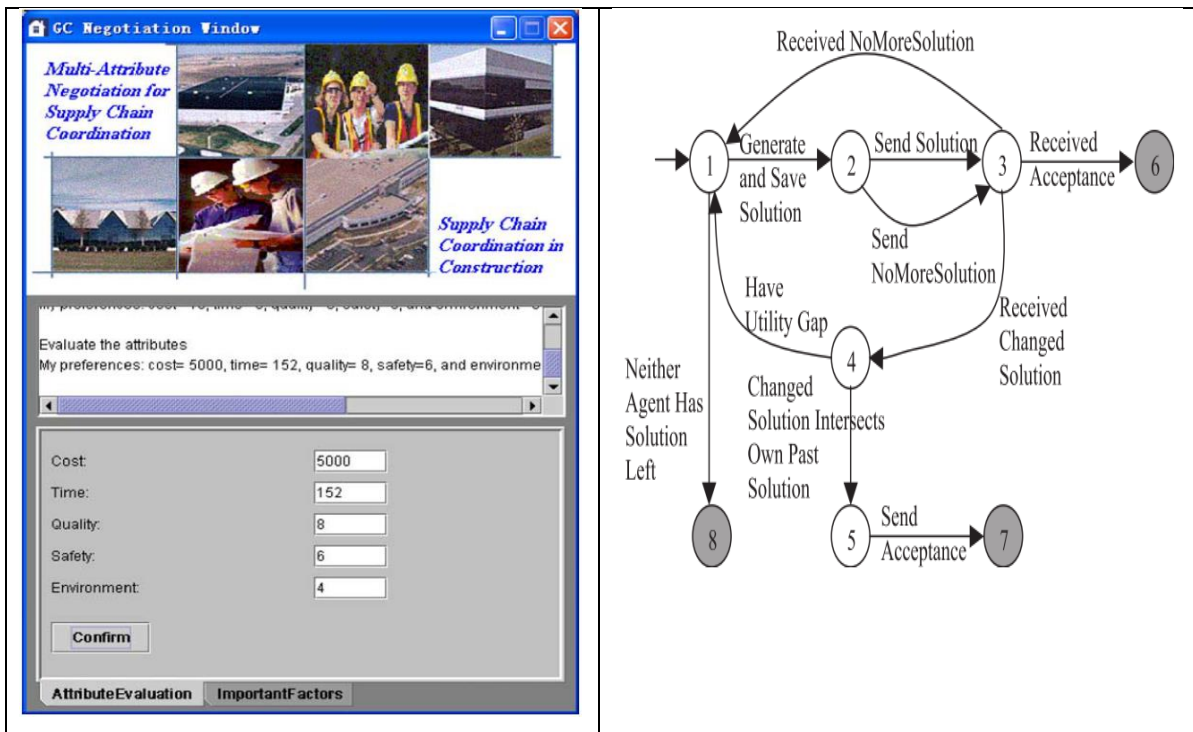


Figure 2.6 A snapshot of user interface of the agent based system on Zeus platform (a), Multi attribute protocol (b), (Xue et al., 2005)

They implemented the framework using “ZEUS” a toolkit for agent based modelling, and tested the proposed system in a hypothetical construction project with only seven activities on a single machine to demonstrate how decision-makers could interact with each other across the supply chain to come up with an acceptable coordination.

Afterward, Xue et al. (2007) extended their previous research and proposed an internet-enabled coordination mechanism for CSC based on the framework that depicted on Figure 2.7. The main advantage of the proposed model is its implementation under the web environment that made it more closely aligned with decentralised decision-making environment.

Recently, Soroor et al. (2012) proposed an automated bid ranking for decentralized coordination of construction logistics. Their model assumes a single-product supply chain to provide a standard component of the product. This approach does not appear to be suitable for a real world project with many sub-projects and many product components.

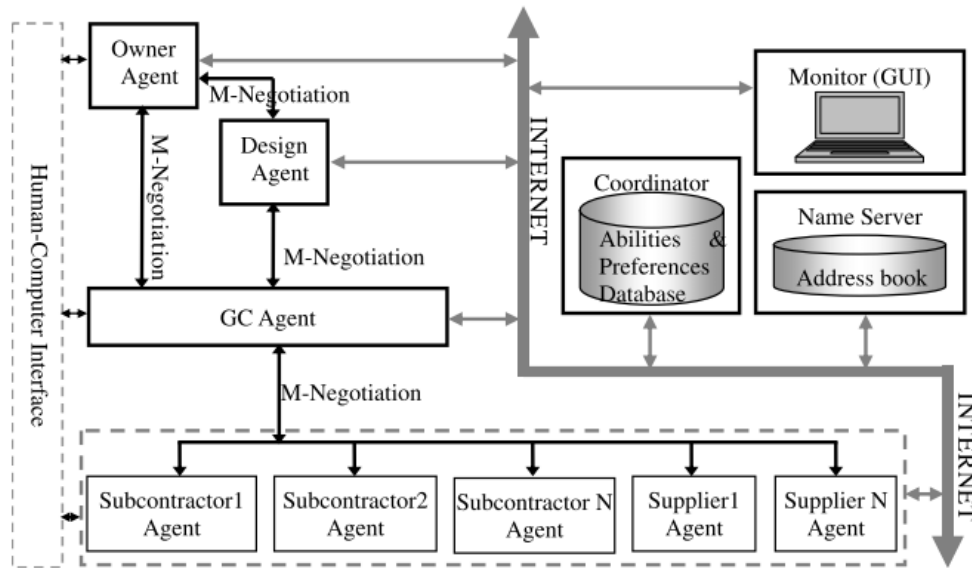


Figure 2.7 An agent based framework for CSC coordination (Xue et al., 2007)

Although these research efforts all used agent based technology to facilitate coordination between agents across the supply chain, there is no research that can optimise the project plan with respect to the common objective functions such as minimization of time or cost or both simultaneously. Furthermore, they did not considered dynamic nature of the multi-project portfolio i.e. the effect of the coming project upon the rest of the portfolio. Finally, this framework only covers the coordination aspects of the supply chain management. Thus, supply chain configuration still needs to be addressed.

2.5.2 Supply chain configuration (design-oriented studies)

Supply chain configuration refers to the studies that determine or optimise the basic infrastructure on which the supply chain performs. Although this field of research is very active in MTS industries for many years, through a thorough literature review, Gosling & Naim (2009) argued that strategic decisions for configuring and designing supply chain for organisations operating in limited volume output and high level of customization in ETO environment have been neglected in comparison with MTS environment. In addition, in the structural design of project supply chain, the implementation of agile systems and the application of lean concepts should have been considered in dealing with uncertainty and dynamic situations (Gosling & Naim, 2009).

In the construction research field, Xue et al. (2010) extensively reviewed selected papers from well-known academic journals in construction management since 1995. The aim of the study was to categorise the research efforts on Collaborative Working (CW) in construction projects. They classified the processes in construction companies delivering across the industry in three main groups:

“1- Traditional construction management (TCM) where independent companies got together by competitive bids and tight contracts. This approach provides no overall direction, reducing everyone involved to defending their own interests. It ignores the need for the well-developed links between workers that are the hallmark of effective teams.

“2- Project Management (PM), a project-based management approach, has been used for resolving TCM failures. Cost, time, and quality are controlled to achieve the client’s objectives in PM. Design build, engineering procurement construction, and build-operate transfer are the three main forms of PM. However, there are many risks frequently incurred which impact the performance of PM.

“3- Partnering (Collaborative Working), where it has various forms such as teamwork, partnership, project alliance, joint venture, strategic alliance, coalition, and SCM.” (see Figure 2.8).

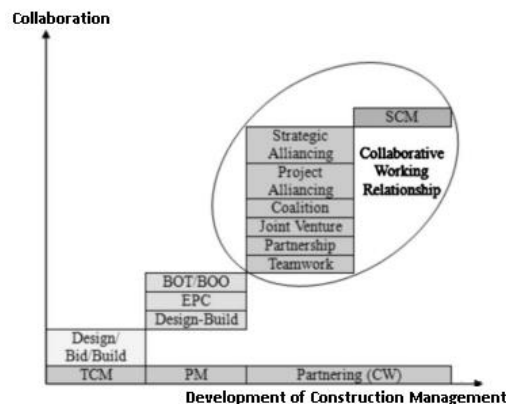


Figure 2.8 Development of CW in construction projects (Xue et al., 2010)

Xue et al. (2010) identified that the business environment and human behaviour are two key factors that impact the performance of CW in construction projects. They categorised the business environment into business strategies and organisational culture. They showed that business strategy plays an important role in pursuing collaborative relationship and improving performance. In addition, by analysing three subareas, general effects of culture, relational contracting, and

organisation learning and knowledge management, they claimed that organisational culture has significant impacts on construction performance. Finally they identified that human behaviour research is another important area of research on CW in construction projects. They recognised trust, tension, conflict, and incentive as four main human behaviours that affect the performance of CW in construction projects. They argued that “trust has been accepted as the most significant factor that effects on effective CW” (Xue et al., 2010).

Although they advocated that “the emergence of prime contracting and the increasing use of framework agreements in the construction sector potentially provide a more supportive climate for SCM than has prevailed traditionally”, they did not find any research to address these issues.

Moreover, referring to the survey made by Gosling & Naim, (2009) in ETO companies, one could realise that although all the researchers believe that the planning and scheduling of the project plays a critical role in all the processes of the project based organisations, they have ignored the integration of an optimised project plan with supply chain design and configuration.

A review of some state of the art research work in supply chain configuration in manufacturing systems was conducted to find out how supply chain configuration is addressed in MTS environments. In particular, the existing current research line in our department namely DIMS technology and its application will be reviewed. Chapter 4 is devoted to this technology and try to assess its capabilities for use in project portfolio supply chain configuration.

While the purpose of this research is to propose a framework for dealing with project portfolio management, the ultimate goal is developing a conceptual framework to find out how construction companies could work collaboratively and reach the optimal reliable supply chain network. Nevertheless, in the real world most construction projects are based on traditional contracting management (TCM) rather than collaborative working. Thus in the next section, a brief review of the methods that mostly used in the bidding process, contracting and subcontractor selection will be provided to understand how practitioners and scholars deal with these widely used issues.

2.5.2.1 Supply chain and subcontractors as sources of risk

As discussed previously, SCM concepts and implementations in project based organisations are relatively new among both scholars and practitioners, particularly in construction supply chains (CSC).

One of the main reasons why the supply networks in project based organisations are not as strong as make-to-stock's SCM, is the existence of different types of risks between the actors across the supply chain. Artto et al. (2008) conducted an extensive literature review along with several semi-structured interviews with construction companies. They identified different types of risks that subcontractors are involved with. They classified the risks that arise in this environment based on four different types of triads as shown in Figure 2.9.

They found that in a single-project environment (including construction), although the projects seem to be independent the risks that are derived from the project supply chain have a strong dependency on the long-term enterprise supply chain risks. They concluded that general contractors need to systematically manage the risks associated with selecting a subcontractor as well as assessing the risk of selecting a group of subcontractors when the relationships between them need to be considered. Therefore, the business network needs to be analysed dynamically as a whole rather than managing the risks statically for each network of individual project.

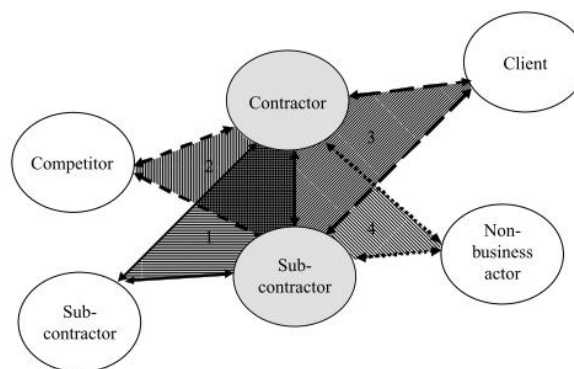


Figure 2.9 Four types of triads based on the subcontractor's relationship with a third actor in a contractor-subcontractor business setting (Artto et al., 2008)

Artto et al. (2008) finally set a series of further research areas in subcontractor selection studies such as: “the estimated frequency of the exchange, type of exchange, criticality of exchange, history of the relationship, state of the buying

company's relationship with the client, subcontractors' relationships to other network actors, state of inter-personal relationships, network positions and power, nature of the network, informal and formal relationships, role stability of network actors, network turbulence, and relationship-specific enablers and barriers”.

Aloini et al. (2012) reviewed 140 papers considering risk management perspective in the construction industry to analyse the factors that cause limitations for SCM implementation. Dealing with risk management that covers assessment, treatment and control, they focused on risk assessment in SCM. They provided an operative framework for risk factors identification and analysis which could help managers in the preliminary phases of the risk management process in the construction SCM (CSCM) implementation. They highlighted the significance of SCM in promoting company performance at different levels (strategic, tactical and operational) by identifying the recent research direction that has changed from the “internal structure to the external inter-organisational processes and relations”. Their study particularly emphasised improving feedback linkages and collective learning. Because of the temporary nature of the construction sites managed by temporary organisations and also because the projects are often scattered geographically, the relationship between actors is weak and suppliers pursue their short term objectives from each project with the effect that partnership agreements are rarely implemented in construction industry. Aloini et al. (2012) categorised risk types in CSCM to “(1) Strategic risks, which affect business strategy implementation. (2) Supply risks or input risks, affecting inflows of resources geared toward operation execution. (3) Operation risks, which affect the company's ability to produce goods or services.” They also explored some other types of CSCM risks including financial, regulatory, legal, and competitive and customer risks. Yet, they claimed that the latter categories are in fact of secondary importance in relation to the problem of SCM adoption, while the emphasis should be on the stability of construction network rather than SCM paradigms, principles and techniques.

With regard to subcontractor selection, they also identified that the responsibility for this decision, usually made at the tactical level, belongs to both clients and contractors when risk of supplier selection is usually measured subjectively.

In the next subsection, a review of the current practices of bidding process and subcontractor selection as two interrelated sub-sections of SCM configuration will be discussed to identify how the risk of supplier selection is mitigated in the construction industry.

2.5.2.2 Bidding process and subcontractor selection in construction industry

The typical phases of a bidding process in a construction projects have been presented by Arslan et al. (2008). They classified the bidding process in 7 phases. It starts from determining the project to bid, understanding the scope and details of the projects, determining the potential subcontractors, estimating the price, determining the bid proposal price and submitting the bid to the client. These phases are shown in Figure 2.10.

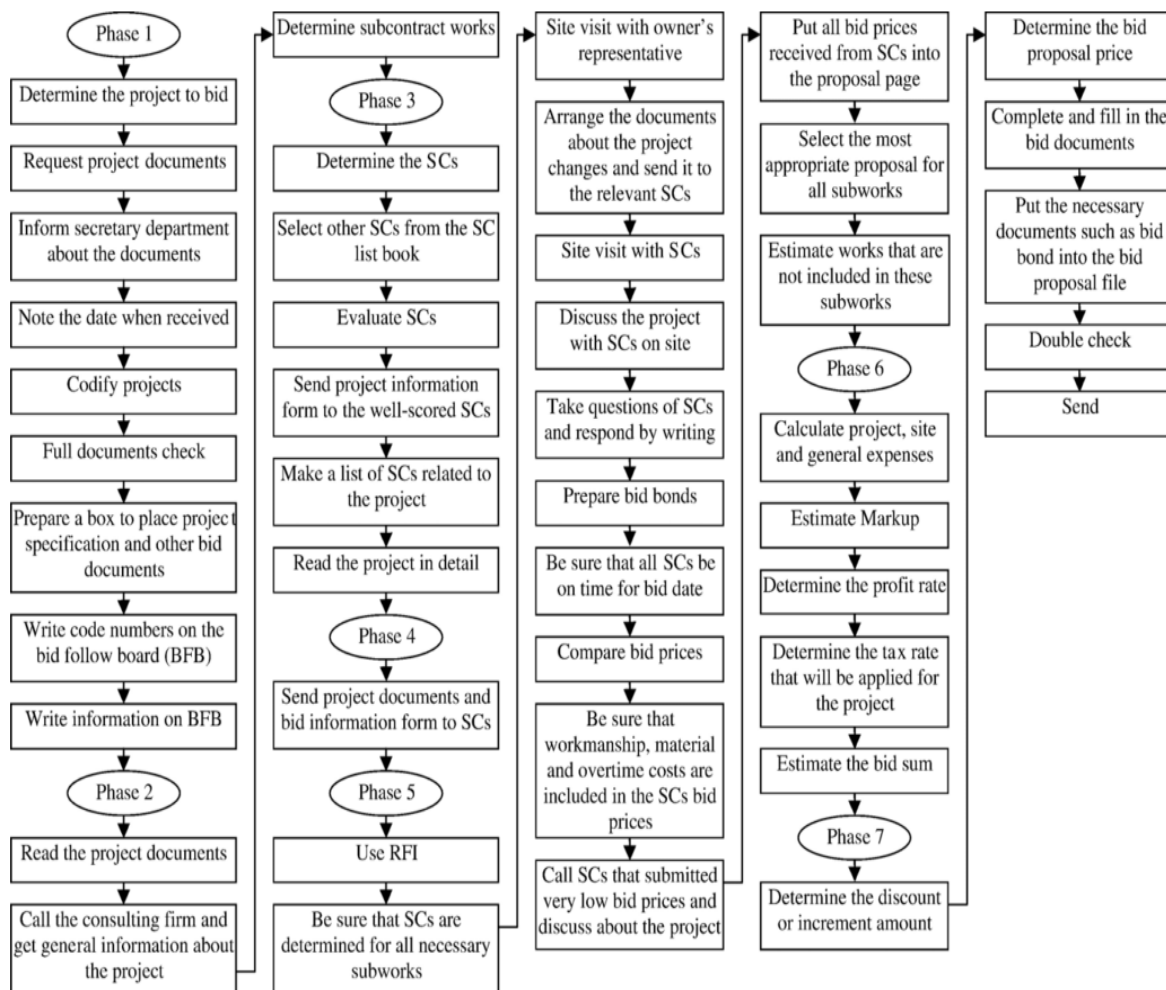


Figure 2.10 Phases during a typical bidding process (Arslan et al., 2008)

The clients usually allow the main contractor between 2 to 6 weeks to conduct these phases while all of the contractors claim that for undertaking these phases at least 12 weeks are required (Laryea & Hughes, 2008).

Each main contractor's bid to the client relies on the collected bids from subcontractors, it is very important for the contractor to select the right subcontractors. In other words, estimating and preparing an appropriate bid proposal is tightly related to the subcontractor selection. So, subcontractor selection plays a critical role in this process.

The low-bid method is a traditional and widely-used approach for subcontractor selection. In the low-bid method "The contract is awarded to the lowest reliable bidder provided the prescribed requirements are met" (Lenin, 2011).

In the case where there are a number of bids received from different subcontractors, there might be some bids that are out of range. Particularly, general contractors may receive some bids that seem to be unrealistic. The reasons why a subcontractor submits such out of range bids could be either accidental or deliberate. In this situation, choosing the low-bid strategy brings risks and difficulties for all of the stakeholders because the subcontractor may not be able to perform the job at the pre-defined cost, time and quality. Therefore some scholars and practitioners propose different methods to help with bid selection (Ioannou & Awwad, 2010). The average bidding method is a good alternative to overcome this drawback. Those who adhere to this method believe that a price close to the average should offer a fair price to the owner and allow the contractor to perform the work at specified quality and at a reasonable profit. More recently, a new method namely "Below Average Bidding" has been proposed by Ioannou & Awwad (2010). This method provides more information choices for selecting one bid among different received bids.

It should be noted that each country has a particular approach that is suit for that country. For instance, in Peru, they use the general concept of the average bid pricing in this way: "if less than three bids are received, a bidding agency may award the contract to the lowest bidder. When three or more bids are received, the average of all bids and the base budget are calculated, and bids that lie 10%

above and below this average are eliminated. A second average of the remaining bids and the base budget is calculated, and the bid closest to but below the second average is the winner” (Ioannou & Awwad, 2010).

Apart from these commonly used approaches there is another stream of subcontractor selection that focuses on qualitative aspects. Some scholars propose methods that consider risk and use qualitative approaches to evaluate subcontractors and calculate a score for each subcontractor in each expertise area (Kumaraswamy & Matthews, 2000). In other words, although subcontractors were selected solely on financial criteria for many years (Ioannou & Awwad, 2010), there are some studies such as (Arslan et al., 2008) which propose a model for subcontractor selection or (Eom et al., 2008) in which they proposed a framework for subcontractor evaluation and management for strategic partnering. Among these models Arslan et al. (2008) proposed a novel methodology so called web based subcontractor evaluation system (WEBSES) as shown in Figure 2.11.

This model seemed to be more relevant for adopting in this study for two reasons. First, the practicality of this model has been tested by practitioners and second it was implemented in a web based system which shows how project managers who are distributed across the different sites of a construction enterprise could have access to the system and evaluate subcontractors.

This model takes into consideration quality, adequacy, cost and time and compare their bids based on a qualitative approach where a Likert scale is used to give a score to each criteria. Finally the overall evaluation score is computed by integrating the weighted scores to give a final score for the subcontractor. Figure 2.11 shows the subcontractor selection process suggested by (Arslan et al., 2008). Although their approaches consider more parameters to facilitate subcontractor evaluation, the time and cost of each bid are evaluated on a qualitative Likert scale. Therefore the model needs some modifications to be used in the holistic hierarchical system framework proposed in this research. This will be discussed in Chapter 6.

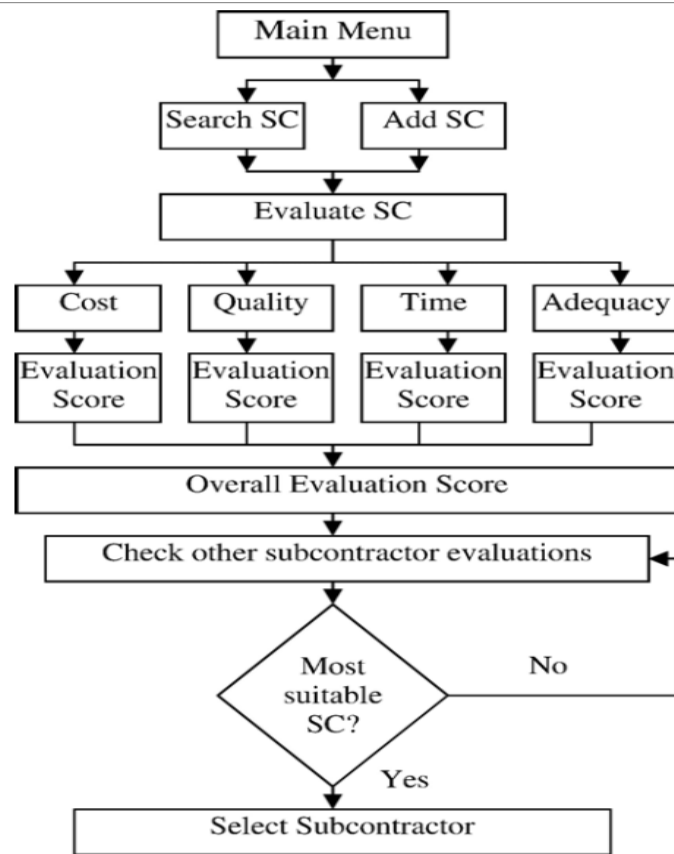


Figure 2.11 Evaluating and selecting sub-contractors using WEBSSES (Arslan et al., 2008)

In the next section, the other layer of hierarchical multi-project planning will be discussed. Project selection is located at the heart of the hierarchical multi-project planning proposed by Hans et al. (2007) in the tactical level. It means that it could play the role of leverage between two other levels. So, understanding that how scholars and practitioners deal with project selection could help to build up a bridge between decisions at the operational and strategic levels.

2.6 Project selection in multi-project management

Project selection is how to choose the best project for achieving more profits for the whole organisation while minimizing the risks of each project. Archer & Ghasemzadeh, (1999) proposed an integrated framework for project portfolio selection and suggested that it could be implemented in the form of a decision support system.

Shakhsi-Niaei et al., (2011) classified the studies on project portfolio selection. They categorised the research into six streams including: benefit measurement

methods, mathematical programming approaches, simulation and heuristics models, cognitive emulation approaches, real options, and ad hoc models. They reported that no methodology is able to accommodate all the project portfolio selection aspects because each has its own advantages and disadvantages.

Wang et al. (2009) claimed that the expected levels of profitability, reliability and feasibility along with project objectives are the deciding factors in the project bid/no-bid decision. They categorised the variety of methods that have been suggested by scholars and highlighted those used particularly in the field of construction industry. An updated version of their table is presented in Table 2.2.

Even though Wang et al. (2009) have presented a comprehensive collection of methods comparing project selection decisions, these writers have neglected the agent based technology and the application of multi-agent system, which is a novel methodology to solve complex and dynamic problems, and which will be considered in Chapter 3.

Table 2.2 Project selection research in the construction industry (developed from Wang et al (2009))

Decision method/model	Description	Published papers
Cost analysis (NPV)	It uses the cost accounting and other relevant information to look for ways to cut costs. Then to choose the project which is the most benefit.	(Okpala, 1991)
Fuzzy preference model	Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise	(Gungor & Arikan, 2000)
Linear and Integer Programming	Linear programming is a technique for optimization of a linear objective function, subject to linear equality and inequality constraints. A kind of mathematical programming whose variables are all or a part integer in the problem.	(Gori, 1996),
Analytical Hierarchy Process (AHP) and Utility Theory	The AHP framework organises feelings and intuitive judgments as well as logic. It improves and streamlines the process by providing a structured approach to decision making.	(Hsueh, Perng, Yan, & Lee, 2007) (Han, Kim, Kim, & Jang, 2008)
Analytic network process (ANP), an extension of AHP	AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network.	(Cheng & Li, 2005)
Constraint programming (CP)	A computer implementation designed for solving constraint satisfaction problems (CSPs)	(Liu & Wang, 2011)

Moreover, looking at theory and practice in the construction industry, Laryea & Hughes (2008) conducted a survey and realised that contractors select a project based on their judgments from the benefit and risk of the involvement in the project. They work on bid preparation when their estimation shows that they can cope with its risk level and reach to the level of confidence that they could perform the job. The contractors usually assess their risk concerned with their capabilities, to evaluate the overall risk that needs to be added in the bid price. This provides a room for manoeuvre to negotiate with the clients, or when the risk is too high reject the bid request. It also helps to avoid investing resources in preparing a bid for a very risky project that may not be submitted.

Taroun (2013) claimed that in order to bridge the current gap between theory and practice, there is an urgent need for models that can reflect practitioners' experiences and practices. As he further continues 'simplicity' lies at the heart of encouraging experts and practitioners to benefit from risk assessment tools. Despite the fact that academics have developed quantification tools (P-I), practitioners do not appeal to use them. He suggests that a simple analytical tool that uses risk cost as a common scale and utilises professional experience could be a viable option to facilitate bridging the gap between theory and practice of risk assessment.

Complex projects have a very sophisticated risk structure. The main challenge is aggregating the individual risks to come up with the proper risk assessment of the project. There are several mechanisms for integrating the individual risks:

- 1- Calculating the average or weighted sum of the individual risk assessments.
- 2- Using Utility Theory, where project utility represents the attractiveness or the risk level of a project; the smaller the project utility the bigger the risk level. In this case, the overall project utility was derived either by a simple or a weighted sum of individual utilities (Taroun, 2013).

The most commonly used methods, for dealing with the complexity of the risk assessment in project level in construction industry, are Fuzzy Set Theory (FST), Analytical Hierarchy Process (AHP) and decision tree that is frequently applied along with a multi-criteria decision making (MCDM) framework. Among these techniques, AHP is one of the frequently used methods that provides a systematic

approach to structuring risk assessment problems for assessing risk impacts and allocating importance weighting. This approach to risk modelling compares the risks of one alternative with others by providing a relative risk scores.

Therefore, considering the simplicity and practicality of the model that is the practitioner’s requirement, taking into account the AHP approach, two models in the literature were identified that are more relevant to distributed construction projects and also were designed under the WWW platform as a tool. Those are (Hsueh et al., 2007) and (Han et al., 2008).

Hsueh et al. (2007) used AHP and utility theory to develop a multi-criteria risk assessment model for construction joint-ventures. In this research, the expected utility value of the project is computed rather than providing a project risk assessment. The solution is obtained by taking into account the higher expected utility value that means the lower level of project risk. This can be seen in Figure 2.12.

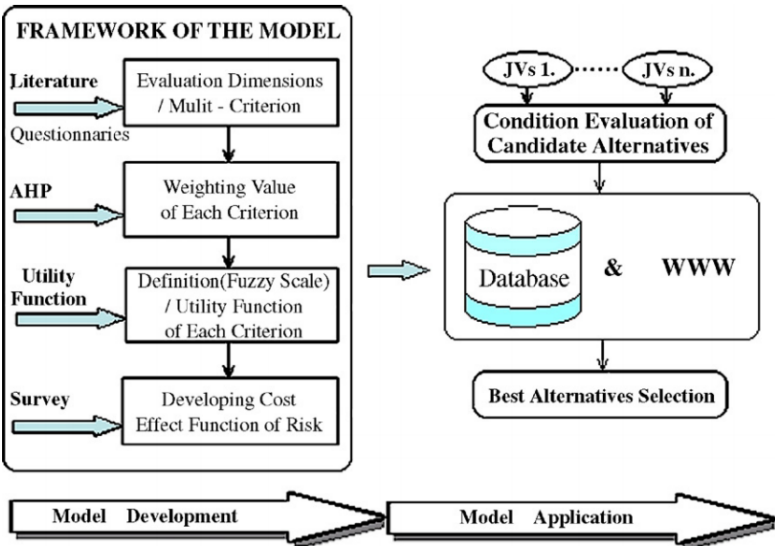


Figure 2.12 The process development (Hsueh et al., 2007)

Han et al. (2008) proposed a web based system for assessing the risks of the projects based on multi-attribute decision model (MADM) methodology. In this method, five main categories were identified and then in the second layer these categories were divided to 35 attributes. The portfolio manager along with its team i.e. project managers as experts could evaluate these attributes and find out which projects are more attractive for the company. This generates a list of ranked CFP

associated to each CA. They investigated 126 sample projects in Korean construction industry and provided a guideline for final selection as follows: “scores above 64% satisfaction would be a definite go zone, while those between 50% and 64% would be a negotiation zone that requires strategies to improve the project condition by focusing on the weakness points or criteria of the utility scores. Scores less than 50% satisfaction was found to be definitely no-go zone” (Han et al., 2008).

2.6.1 Adopting a model for project/bid selection

Although both above discussed models utilised AHP and utility theory, Han et. al’s model seems to be more relevant, accurate and practical. There are two reasons to choose the latter model in this study. First, in contrast with the former model, it is utilised the Simple Multi-Attribute Rating Technique (SMART) for weighting the lower-order 35 attributes while the former used the eigenvalue method for weighting all of the 25 identified attributes for pre-joint venture stage, which is more complicated for practitioners and it is more relevant to the international construction project. Moreover, Han et al, tested the AHP model with the profit prediction model and found consistency in the results.

Thus, the model proposed by Han et al. (2008) was adopted to be utilised in the integrated framework subject to some modifications that will be discussed in Chapter 6. The proposed modifications was made due to integrating project selection decision with scheduling decisions which is at the operational decision making level where several projects in different sites need to be scheduled based on a prioritisation technique. This is needed to resolve the conflicts in resource allocation in multi project scheduling problems.

In the next chapter, the multi project scheduling problem will be comprehensively reviewed and the required characteristics of the appropriate model in the construction industry will be addressed.

2.7 Summary

In this chapter, the hierarchical multi-project planning and control was discussed. A holistic integrated framework that covers project scheduling, project selection and

supply chain management (coordination and configuration) was illustrated. Since understanding the background of these concepts is vital for proposing an appropriate methodology in the field of construction management, this chapter also looked at studies first on supply chain management both in operational (coordination) and strategic (configuration) levels and then reviewed project selection studies. The review identified existing gaps and provided the required insight for gaining the further research objectives. Project scheduling that lies at the heart of the hierarchical multi-project planning, will be discussed extensively in Chapter 3 where different dimensions of studies in this area will be explored. These literature reviews help to identify the gaps within and between the domain and find out how a practical and applied hierarchical multi-project planning could integrate supply chain management with project selection and project scheduling in a holistic approach. This will be highlighted at the end of Chapter 4.

CHAPTER 3 MULTI-PROJECT SCHEDULING

3.1 Introduction

The multi project scheduling problem is concerned with allocating the resources and scheduling several projects. As discussed briefly in the previous chapter, these decisions need to be integrated with other decisions in the hierarchical multi project planning framework. This chapter aims to review the literature in the field of multi project scheduling. The chapter reviews the available research works and highlights the gaps of the knowledge in the multi project scheduling problems in the construction industry.

It focuses on resource constrained multi-project scheduling problem (RCMPSP) that is a generalisation of resource constrained project scheduling problem (RCPSP). Therefore, prior to reviewing the literature in RCMPSP, the RCPSP will be reviewed in Section 3.2 to provide the basic concepts of the project scheduling and to classify this problem and finally to discuss which available model is more suitable for adopting in this study for individual projects in the construction industry. Then in Section 3.3, a literature review in centralised multi-project scheduling problem will be presented. Section 3.4 is devoted to a comprehensive literature review in decentralised multi-project scheduling problem. At the end of each section the available models are evaluated for their suitability for a hierarchical multi-project planning framework and to identify the gaps remaining for further work.

Later in the chapter in Section 3.5, using a matrix/table analyses, a gap analysis will be provided to identify which approach is more suitable for the construction industry, which model can be adopted and what kind of modifications need to be applied. This will shed light on the rest of the research. The chapter will end with a summary.

3.2 Single-Project scheduling

Reyck & Herroelen (1999) categorised some of the most important related problems in the single project scheduling (see Table 3.1) over the half a century. This table categorises the problems with respect to their mode, i.e single mode or multi-mode (multiple renewable resource and (multiple) non-renewable resource), consideration of generalized precedence relations (CPM precedence constraints, minimal time lags or minimal as well as maximal time lags).

Table 3.1 A classification of project scheduling problems (Reyck & Herroelen, 1999)

Single mode		Multiple mode			
No resource types	Multiple renewable resource types	1 non-renewable resource type	1 renewable resource type	Multiple renewable and non-renewable resource types	
no trade-offs	no trade-offs	time/cost trade-offs	time/resource trade-offs	time/cost trade-offs	time/resource trade-offs
ZERO-LAG FS	CPM/PERT	RCPSPP	DTCTP	DTRTP	MRCPSPP
MIN SS, SF, FS, FF	PDM	GRCPSP	GDTCTP 1	GDTRTP 1	GMRCPSPP
MIN + MAX SS, SF, FS, FF	MPM	RCPSPP-GPR	DTCTP-GPR	DTRTP-GPR	MRCPSPP-GPR

Table 3.2 List of abbreviations (Reyck & Herroelen, 1999)

The abbreviation of each problem type is presented in the appropriate cell of the table and the full name of each problem type abbreviation is reported in Table 3.2. In this section, some of these problems are reviewed and their solutions are discussed.

Problem type	Description
CPM/PERT	Critical Path Method/Program Evaluation and Review Technique
PDM	Precedence Diagramming Method
MPM	Metra Potential Method
RCPSPP	Resource-Constrained Project Scheduling Problem
GRCPSP	Generalized Resource-Constrained Project Scheduling Problem
RCPSPP-GPR	Resource-Constrained Project Scheduling Problem with Generalized Precedence Relations
DTCTP	Discrete Time/Cost Trade-off Problem
GDTCTP	Generalized Discrete Time/Cost Trade-off Problem
DTCTP-GPR	Discrete Time/Cost Trade-off Problem with Generalized Precedence Relations
DTRTP	Discrete Time/Resource Trade-off Problem
GDTRTP	Generalized Discrete Time/Resource Trade-off Problem
DTRTP-GPR	Discrete Time/Resource Trade-off Problem with Generalized Precedence Relations
MRCPSPP	Multi-Mode Resource-Constrained Project Scheduling Problem
GMRCPSPP	Generalized Multi-Mode Resource-Constrained Project Scheduling Problem
MRCPSPP-GPR	Multi-Mode Resource-Constrained Project Scheduling Problem with Generalized Precedence Relations

One of the basic problems in this classification looks at both precedence and resources constraints. It is known as resource-constrained project scheduling

problem (RCPSP). RCPSP is associated with single-items such as construction projects and/or producing capital goods in engineering-to-order (ETO) or make-to-order (MTO) companies where scarce resources have to be allocated to dependent activities (Brucker et al., 1999).

RCPSP can be also extended to multi-mode models. In single-mode models, there is only one option for conducting each activity whereas in multi-mode ones there is more than one option for allocating different types of resources to the activities causing the tasks to complete faster or slower. Multiple activity modes in turn give rise to several types of trade-offs between (a) the activity duration and its use of resources (time/resource trade-off), (b) the activity duration and its cost (time/cost trade-off), and (c) the quantity and combination of resources employed by the activity resource/resource trade-off).

The reader could refer to Węglarz et al. (2011) where they provided a comprehensive survey regarding single-project, single-objective, deterministic project scheduling problems in which activities can be processed using a finite or infinite (and uncountable) number of modes concerning resources of various categories and types. They provide a detailed literature review based on different basic characteristics that were mentioned in Section 2.2 i.e. resource types, activities, objectives, and schedules. Their study included most important problems mentioned in Table 3.1. They also highlighted the models and solution approaches across the class of problems and finally provided the directions for future research. As a summary of their survey, they reviewed plenty of research works regarding the establishment of heuristic and meta-heuristic algorithms for the above-mentioned problems (Table 3.1). These approaches are generally categorized by single- and multi-pass priority-rule-based scheduling, simulated annealing (SA), genetic algorithms (GA), tabu search (TS) and Bender's decomposition. Furthermore, they reviewed recent studies where ant colony optimization, particle swarm optimization (PSO) and combinatorial PSO or CPSO have been used. In the next subsections, a brief review of the literature is provided for these categories. It worth noting that more recently Zhou et al. (2013) conducted a survey on single project scheduling problem in construction industry in which the same approaches were reviewed.

3.2.1 Single-mode problem

The simple RCPSP model is a single-mode problem with observation of precedence constraints between activities which also considers scarce resources. RCPSP has been known as an “NP-HARD” problem because it is a generalization of the “Job Shop Scheduling Problem (JSSP)” -(Kolisch, 1996).

The pioneering work of RCPSP by Johnson (1967) proposed a branch-and-bound algorithm for gaining an exact solution for this problem. Afterwards, the variety of enumerative methods have been developed by (Christofides et al., 1987; Patterson et al., 1989) and enhanced by Demeulemeester & Herroelen (1997).

Apart from exact algorithms, there are a number of heuristic approaches that have been developed for solving the model. The priority-rule based scheduling methods have been widely designed and tested. Although they are very easy to apply and can quickly obtain results, the average deviation from the optimal value of the objective function is unsatisfactory. Thus, other heuristic methods such as truncated branch-and-bound, sampling techniques and local search techniques are being generated and their computational capabilities are being compared with each other based on speed and performance (Węglarz et al., 2011).

3.2.2 Multi-mode RCPSP

In the previous section, the single-mode problem (RCPSP) was introduced. In fact, the single-mode problem is a special and simplified case of multi-mode RCPSP, which is closer to the reality of the project environment. In multi-mode problems, the modes indicate alternative combinations of resources and their quantities to carry out the activities. For instance, an activity could be conducted quicker by increasing the quantities involved in operation (time-resource trade-off) or by increasing the demanded quantities of some resources, while decreasing the demanded quantities of other resources, the resource substitution (resource – resource trade-off) can be investigated.

The methods applied so far for the exact solution of the problem are extensions of branch and bound procedures originally proposed for the single-mode RCPSP. In fact, most of the exact algorithms apply implicit enumeration with branch and bound (Kolisch & Padman, 2001). For instance, Sprecher & Drexel (1998) improved

the precedence tree algorithm introduced by Patterson et al. (1989) by including new bounding criteria. Furthermore, Demeulemeester & Herroelen (2002) proposed branch and bound algorithm to solve the problem exactly.

On the other hand, there is a variety of heuristics and meta-heuristic methods to solve large scale project instances. Among them GA is used more frequently due to its characteristics that make it suitable for large scale problems.

For example, Wuliang & Chengen (2009) proposed a multi-mode RCPSP that is based on genetic algorithm and provides a time-cost trade-off. This model considers several important requirements that have been neglected in previous research. These essential requirements can be considered as: i) taking both the direct and indirect cost for the project into account, ii) limitation of renewable resources used in the project iii) each activity should be performed by a selected mode. The mode is a method of performing an activity to shorten the performance time of the activity by spending more direct costs.

Although the assumptions of the proposed model are more realistic than others, it assumes that “all the renewable resources are monopolized” to a single project and they cannot be shared with other projects. Therefore, the model suggested by Wuliang & Chengen (2009) is not suitable for a resource constrained multi-project scheduling problem (RCMPSP).

3.2.2.1 Discrete time-cost trade-off problems

Among different sub-problems of the multi-mode RCPSP, discrete time-cost trade-off problems have been extensively studied particularly in the construction industry by both scholars and practitioners. The review of literature reveals that three main versions of discrete time-cost trade-off problem (DTCTP) exist which are the budget problem (DTCTP-B), the deadline problem (DTCTP-D) and complete DTCTP curve. Considering a set of modes and a project deadline of δ in (DTCTP-D), each activity is designated to one of the possible modes. In this case, the total cost has to be minimized. In contrast, the budget problem seeks to minimise the project duration while meeting a given budget (B). In the third case, the complete time/cost trade-off function for the total project must be computed. The curve is constructed based on all efficient points (T,B) so that with a resource limit B a

project length T can be obtained and hence no other point (T', B') exists for which both T' and B' are smaller than or equal to T and B .

The solution algorithms for DTCTP has been addressed for many years. While some scholars provided mathematical programming models such as dynamic programming, linear programming and integer programming LP/IP hybrid, there is an argument that these methods cannot efficiently obtain optimal solutions for large-scale networks (Feng et al., 1997). In addition, they may easily get trapped into local optima (Zheng, 2004). Because of these drawbacks of exact solution approaches, many scholars use heuristic and metaheuristic algorithms such as tabu search approach and genetic algorithm (GA). A comprehensive survey of different approaches to single objective DTCTP is presented in Węglarz et al. (2011).

Apart from these studies that consider single objective function, there is a growing attention to the multi objective models and its solutions in single project construction scheduling studies (Zhou et al., 2013). In multi objective DTCTP minimisation of both cost and time as two objective functions are considered. These include Ant Colony optimization (ANC) (Xiong & Kuang, 2008), the Particle Swarm Optimization (PSO) (Yang, 2007) and Harmony Search (HS) optimization (Geem, 2009) methods. These have been applied to gain the optimal Pareto-set solution. The multi objective genetic algorithm is one of the most applied methods in the literature (Feng et al., 1997; Zheng, 2004; Ghoddousi et al., 2013) due to its performance in comparison with others.

One of the important derivations of the DTCTP is generalized discrete time cost problem GDTCTP. In this model different types of precedence constraint including Start-Start, Finish-Finish and Start-Finish have been added to the above-mentioned basic model to accommodate the special characteristics of the construction industry (Sakellaropoulos & Chassiakos, 2004; Chassiakos & Sakellaropoulos, 2005; Hebert & Deckro, 2011). Hebert & Deckro (2011) integrated Excel Solver with Microsoft project to solve the problem optimally in a sample project with a small number of activities, but failed to demonstrate a Pareto-front. Chassiakos & Sakellaropoulos (2005) proposed heuristic and meta heuristic solutions for the problem in which a single objective model needed to be solved

several times to obtain a pareto front curve. Considering generalised precedence constraints as well as minimisation of time and cost make the model more suitable for real world construction projects. Thus it seems that among several studies in single project scheduling problems, the model proposed by Chassiakos & Sakellaropoulos (2005) is more relevant to be adopted for constructing an integrated framework for real world construction project planning in the main contractor organisations.

According to the papers reviewed in the field of single project scheduling, Table 3.3 provides a summary of the discussed features and highlight advantages and disadvantages of the papers reviewed.

Table 3.3 Summarising the literature review in single project scheduling

Study type	Authors	Pareto-front curve	Generalised precedence constraints	Solution algorithm
1	Johnson (1967) Christofides et al. (1987) Patterson et al. (1989) Demeulemeester & Herroelen (1997)	No. The models are single mode RCPSP.	No	Exact solution algorithm. Not suitable for large size project.
2	Kolisch & Padman (2001) Sprecher & Drexl (1998) Patterson et al. (1989) Demeulemeester & Herroelen (2002)	No. But they are multi-mode RCPSP.	No	Exact solution algorithm. Not suitable for large size project.
3	Wuliang & Chengen (2009)	Yes. It is multi-mode RCPSP.	No	Single objective GA. Due to some limitations, it was not advised for using in multi-project problem environment by the authors.
4	(Xiong & Kuang, 2008)	Yes. The model is a discrete time cost trade-off problem.	No	Ant Colony optimization (ANC)
5	(Yang, 2007)	Yes. The model is a discrete time cost trade-off problem.	No	the Particle Swarm Optimization (PSO)
6	Feng et al. (1997) Zheng (2004) Ghoddousi et al. (2013)	Yes. The model is a discrete time cost trade-off problem.	No	Multi Objective GA.
7	a.Sakellaropoulos & Chassiakos, (2004) b,Chassiakos & Sakellaropoulos (2005)	Yes. The model are a discrete time cost trade-off problem.	Yes	They are single objective function models. a. It is solved by Lindo (exact method). b. It solved by a heuristic method.
8	Hebert & Deckro (2011)	No. The model is a discrete time cost trade-off problem.	Yes	LP model solved by Excel Solver integrated with Microsoft project. It doesn't provide pareto

Although the above-mentioned research works (particularly (Chassiakos & Sakellaropoulos, 2005) proposed heuristic and meta heuristic solutions for the problem, to the best of the author's knowledge, there are not any studies considering multi objective optimization that result in a pareto-front curve. Thus this model could be modified to be used in the integrated multi project planning framework for the construction industry.

Based on the literature reviewed of the single project scheduling problems, the multi-project scheduling problems will be reviewed. First, the next section looks at the traditional methods namely centralised approaches and then Section 3.4 examines the decentralised approaches.

3.3 Centralised multi-project scheduling (traditional approach)

As it was stated earlier, most of the firms work in multi-project business environment. Therefore scrutinising the RCMPSP seems to be more important and relevant for industry. There are two approaches for modelling RCMPSP, i) creating a super-network ii) modelling the problem based on individual projects. In this section 3.3, each of them has been described by reviewing relevant literatures.

The most common technique to deal with multi-project planning and scheduling is to comprise single project networks into a "super-network" by adding a "super-source" and a "super-sink," while a share pool of resources is considered (Hartmann & Briskorn, 2010). This means that the separate projects are artificially combined into one large project for scheduling purpose. This approach (see Figure 3.1) has been firstly proposed by Pritsker et al. (1969), when they provided an exact method by using a zero-one programming approach.

Integrating multiple projects in a single network has great advantages. This provides a formal basis for the application of scheduling methods for single projects as well as to the case of multiple projects (Hartmann & Briskorn, 2010).

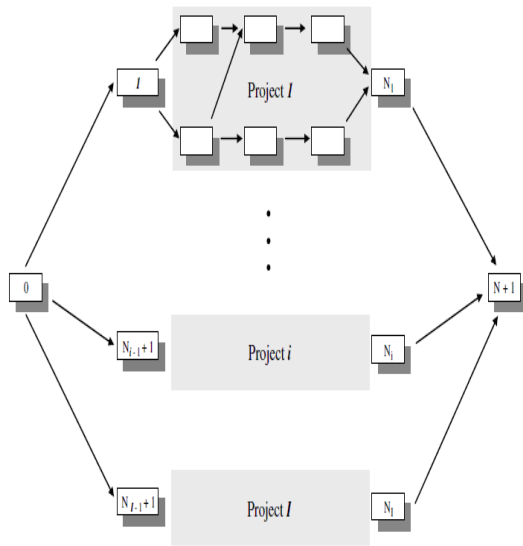


Figure 3.1 Super-project network (Gonçalves et al., 2008)

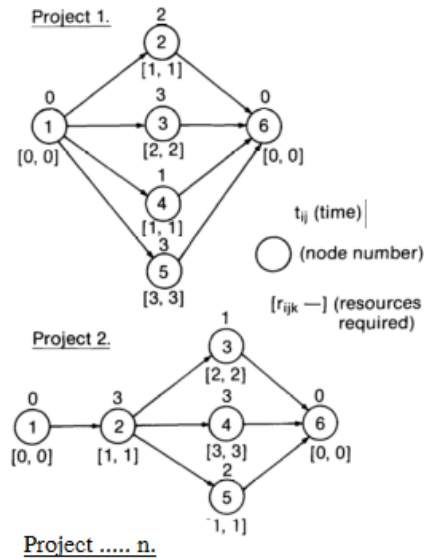


Figure 3.2 Multi-Individual project Network (Kurtulus, 1985)

Using super-network approach, Vercellis (1994) tackled the multi-project planning problem in multi-mode conditions. He decomposed projects based on two sets of constraints i.e. i) precedence constraints among the set of projects, and ii) the set of constraints which partition the available resources among the different projects. Then he relaxed these two groups of constraints by introducing two sets of multipliers and presented Lagrangian relaxation of the RCMPSP. Consequently, he decomposed RCMPSP to the n separate sub-problems, one for each single project. It is clear that each of the RCPSP is easier to solve rather than the original one RCMPSP. Then one could use either exact methods based on dynamic programming, in the case of instance of moderate size, or by approximation heuristics for a higher number of variables for solving the decomposed problem. For instance, Gonçalves et al. (2008) proposed a heuristic approach for modelling and solving RCMPSP. They designed and analysed a genetic algorithm for the resource constrained multi-project scheduling problem. They considered only finish to start precedence constraints with zero-time lag between activities in all projects and a set of renewable resources in a single-mode problem with a combinatorial objective function. They developed an algorithm that combines a genetic algorithm with a schedule generation procedure that creates parameterised active schedules. They applied “parametrised active schedules” to reduce the solution space. They applied their algorithm on a set of test problems with maximum 50 projects and

6000 activities. They tested the effectiveness of the proposed genetic algorithm by using three solution alternatives for schedule generation parameters. In the computational experiments, they showed that the values obtained by implementing their GA approach, are very close to the optimum value.

As the review of literature shows, it seems that multi-project multi-mode scheduling problems with generalised precedence constraints have been rarely addressed based on super-network modelling. It could be due to a huge complexity of the modelling approach which most of the scholars avoid facing with this problem by implementing super-network methodology. In order to overcome the complexity of involving with a single super-network problem, some scholars have started to develop truly multi-project problems rather than mixing them together as a single super project network.

It means that, some scholars consider each single project among the portfolio independently. Each project has its own dedicated resources while the entire portfolio has some shared resources in a common pool. A centralized manager could decide to allocate the shared resources to each project. In fact, the projects are limited only through their dependence upon a common pool of available resources of each category. Under the umbrella of this idea, particular multi-project scheduling methods that are mostly heuristic in nature, are developed and implemented in research works. Figure 3.2 shows the multiple projects problem.

Kurtulus & Davis (1982) as a first study based on multi-individual-project network considered multi-project instances whose projects had between 34 and 63 activities and resource requirements for each activity between 2 and 6 units. They considered the total project delay, where the delay of each project is measured as the difference between completion time in the actual schedule and completion time in the resource-unconstrained critical path case.

They proposed six new priority rules and compared them with three other priority rules which were previously used by scholars for solving their models. They reported the computational experience regarding minimization of total project delay. They showed that the "truly multi-project" approach has better performance than "super-network" approach because of the two best performing rules SASP and MAXTWK. Kurtulus (1985) extended this approach by defining several

functions that assign different delay penalties to the projects. He proposed four new priority rules based on penalties delays. As one of the most important conclusions, the priority rule maximum penalty was considered the best algorithm to minimize the sum of the project weight delay.

Table 3.4 shows the summary of most of priority rules which are broadly applied by scholars since then in heuristic algorithms.

Table 3.4 Priority rules in heuristic methods

Priority Rule	Explanation
FCFS	First Come First Served
SOF	Shortest Operation First
SASP	Shortest Activity From the Shortest Project
LALP	Longest Activity From the Longest Project
MINSLK	Minimum Slack First
MAXSLK	Maximum Slack First
MINTWK	Minimum Total Work Content
MAXTWK	Maximum Total Work Content
MINLFT	Minimum Latest Finish Time
MAXDUP	Maximum duration and penalty
MAXTOP	Maximum total duration Penalty
MAXPEN	Maximum Penalty
SLKPEN	Simultaneously slack and penalty

Kumanan et al. (2006) proposed the use of a heuristic and a genetic algorithm for scheduling a multi-project environment. They considered multiple projects the activities of which can be performed in one of several modes.

They designed each chromosome as a project sequence or scheduling order for resource allocation. In other words, each chromosome denoted the priority of each project for resource allocation. The objective function i.e. so-called fitness function was to minimize the makespan of the all projects. Meanwhile, the priority role for allocating a scarce resource at a time instant was determined in the chromosome, if there was a conflict for allocating the same resource to two different activities in a project, and then gave preference to less slack activity. After applying crossover and mutation, evaluation was performed to obtain the makespan of the schedule derived from each chromosome. Then, all chromosomes were sorted into

ascending order to define the best one, provided the optimal multi-project schedule.

They validated their approach by comparing its results with four other priority rolls such as LCFS, SPT, FCES and EDD.

In contrast with the Gonçalves et al. (2008), it could be understood that Kumanan et al. (2006) did not use super-network approach. Although they used a “true” multi-project approach for modelling the problem, there was only one decision maker dealing with decisions for resource allocation and scheduling activities across all projects. This is referred to centralised scheduling problem as discussed earlier in this section.

Although Reyck & Herroelen (1999), Zhou et al. (2013) and (Hartmann & Briskorn, 2010) provided a comprehensive survey of RCPSP/RCMPSP, they did not consider the recently proposed research studies based on decentralised multi-project planning. More precisely, in all of the above-mentioned research works the RCMPSP has been taken into consideration by a centralized decision maker where all the projects are managed by a single manager. It is clear that, in the real world this assumption is far from reality. Usually, in each multi-project firm there are several project managers who manage one or two projects. They compete with each other to gain resources, skills etc. to finish their projects on time and on budget. They make their decisions independently and they are to some extent autonomous. However, their decisions exert influence on the entire portfolio and other related projects. In order to understand the methods and models in decentralised multi project planning environments the relevant literature will be reviewed in the next section.

3.4 Decentralised multi-project scheduling problem (DMPSP)

As discussed above, there are two types of decision-making approaches for coping with RCMPSP i.e. centralised and decentralised methods. The purpose of this section is to review the concept and studies in the field of the decentralised scheduling problem.

The idea of decentralising multi-project scheduling problem goes back to the year 2003 when Lee et al. (2003) claimed that, as a result of large improvement in technology of Internet and globalization of the business, multi-project firms work in a more distributed way both organisationally and geographically. They claimed that centralised project management where all projects are managed by a single manager is not suitable in these cases. They defined a new name for this kind of project environment. This is the “decentralised or distributed multiple projects (DMP)” environment. They proposed Decentralized Multi-project Scheduling Problem (DMPSP). It is a dynamic complex combinatorial approach, which employed Multi-Agent Systems (MAS) to simulate the genuine multi-project problem. It is a distributed approach based on informational and geographical aspects in project portfolio organisations.

Therefore, DMPSP is a generalization of RCMPSP where renewable resources are divided into two types. One type is local resources, which are under control and supervision of each single project manager who makes the decisions locally. The other type is global resources; these are resources that are shared among several projects. They are therefore under the control and supervision of portfolio manager or coordinator who is the global decision-maker. The local resources are dedicated to the projects while global resources could be allocated to any project based on the decisions of portfolio manager.

In contrast with centralized multi-project scheduling they highlighted some characteristics of DMPSP including i) having a multi decision maker ii) incomplete decision making information iii) local decision content and iv) coordination for multiple decision objectives (Wang et al., 2011).

In the following sections, first the characteristics of multi agent modelling will be discussed. Then, the methodologies of application of MAS in context of multi-project scheduling will be classified and described. Finally the drawbacks of the current models will be highlighted.

3.4.1 Why use multi agent methods for DMPSP?

Through reviewing the literature, it was found that little research has been carried out with regards to the dynamic modelling of RCPSP/RCMPSP, where new projects can be introduced into the portfolio and some of them are finished across

the unbound time horizon. Considering the dynamic nature of the real world multi-project scheduling problem, some studies have been conducted by using Petri-Net simulation approach for scheduling problems (Reddy et al., 2001), (Kao, Wang, Dong, & Ku, 2006).

Due to the huge improvement in knowledge of artificial intelligence within last decade, the application of agent-based simulation (ABS) (North & Charles, 2007) and Multi-agent system software (MAS) (Brenner et al., 1998) are currently known for solving different complex problems such as Supply Chain Management and Manufacturing Systems ((Swaminathan et al., 1998), (Arbib and Rossi, 2000) and (Zhang et al., 2007)). The survey conducted by Jahangirian et al. (2010) shows that agent-based simulation (ABS) has been increasingly used in the field of multi-project scheduling in last few years. Knotts et al. (2000) were the pioneer researchers who initially used the MAS for single project scheduling problems.

Agent based modelling is a distributed system composed of a set of self-contained problem-solving entities called agents. Characteristics of each agent are: i) it operates by collecting data from the environment, analysing the information and applying strategies in order to achieve its goal. ii) It has incomplete information. According to the characteristics of each agent, an agent based model performs based on following conditions: i) the system is not controlled centrally, ii) the computation is asynchronous, iii) the data is decentralised (Confessore, Giordani, & Rismondo, 2007).

Indeed, complex problems in a system could be separated into simpler sub problems by using agent-based systems. This makes the control easier and improves the system performances. In addition, MAS is able to admit “dynamic and uncertain information, and has some intelligence, adaptability and robustness” (Ren & Wang, 2011).

As a project portfolio (e.g. construction industry), the organisation and its supply chain/ subcontractors are very complex, the essence of each project might be different from the others for example some projects are finishing while some others are under bidding process (i.e. dynamic nature). The above-mentioned characteristics of MAS therefore make it suitable to be used for solving distributed multi-project management problems.

3.4.2 Research works in DMPSP

As was discussed above, Lee et al. (2003) were the first researchers who propose the use of an agent based method in multi-project problems. They argued that a decentralised multi-project (DMP) environment could have several goals where the company has several (shared) resource divisions. They claimed that there could be different types of goals. For instance, while the objective of each resource division could be maximizing the utilization of its resources, the objective of the project groups could be minimizing its risks of not completing the project on time. They proposed a market-based multi-agent system model for DMP. The structure of their model has been established by five types of agents. These are:

- i) Project manager (PM), who is responsible for the achievement of the project, works in coordination with the individual task agents. The PM maintains the project activity network and its milestones. Task agent (TA), who works as a buyer in a resource time-slot market maintains required resource types, task durations, and current schedules.
- ii) Resource manager (RM), who is in charge of monitoring and coordinating a set of resources.
- iii) Resource agent (RA), who interacts with TAs as a seller, maintains its own schedule.
- iv) Coordinator (CO), who is responsible for coordinating multiple resource allocation markets in the virtual market model.

These agents interact with each other in a virtual market environment through a negotiation mechanism which they called the precedence cost tatonnement (P-TATO). The agents seek optimal solutions for minimizing weighted tardiness based on Drexl (1991). Figure 3.3 shows the organisation of these agents.

The optimal resource schedule is determined by RAs based on the utility function, which is maximized by a heuristic algorithm. The procedure comprises of three steps:

“(1) initial sequencing based on utility distribution using heuristic rules, (2) calculating the optimal allocation in the given sequence using dynamic programming (DP) and (3) repeating pair-wise exchanges based on a heuristic rule and step 2 until no further improvement can be made”.

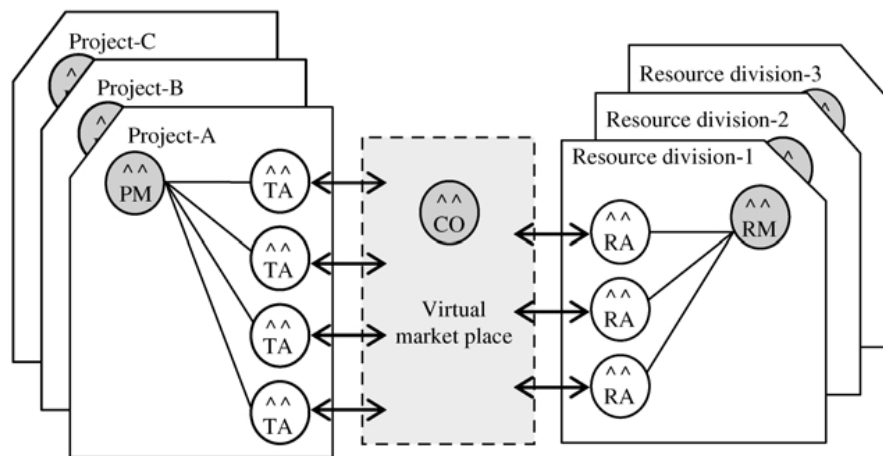


Figure 3.3 A MAS organisation of DMPSP resource, control system (Lee et al., 2003)

Conducting an empirical analysis based on the data generated by an instance generator namely ProGen, they showed that in comparison with an IP formulation proposed by (Drexler, 1991) solved using LINDO, their proposed approach is suitable for small size problems.

It should be noted that in their model they have not considered any local resources meaning that request for bid could be made by all of the resource divisions for all of the projects.

Confessore et al. (2007) illustrated a decentralised resource constrained multi-project scheduling problem (DRCMPSP). In this problem, a set of n projects has to be planned concurrently. The following data is available for each project: an earliest release date, a set of activities, precedence constraints for activities and a set of local re-newable resources. There are also some global renewable resources, which have to be shared by all projects. Each project is planned in a decentralised way by a project manager, an autonomous and self-interested decision maker. He has the local objective to minimise the schedule length (i.e., makespan) of his project. The makespan of a project is defined as the difference between the project's finishing date and the project's arrival date. Actually, the activities of different projects may need the same shared resource simultaneously. Therefore, the local objectives of the managers are usually in conflict with one another. Confessore et al. (2007) dealt with the situation where the capacity of shared resource is equal to one and there is only one type of shared resource.

They implemented multi agent systems for solving DRCMPSP. For conducting this, they defined two types of agent:

“i) the project managers, who have to schedule their project activities requiring the shared resource in specific time slots and
 ii) a coordinator agent, who is responsible for allocating the shared resource time slots to project managers, and, hence, for solving shared resource conflicts among projects” Confessore et al. (2007).

Figure 3.4 illustrates the multi-agent system functional schema of their approach. As it is described, the objective of their model was to seek a precedence and resource feasible schedule for all the activities of each project in such a way that the makespan of each project is minimized.

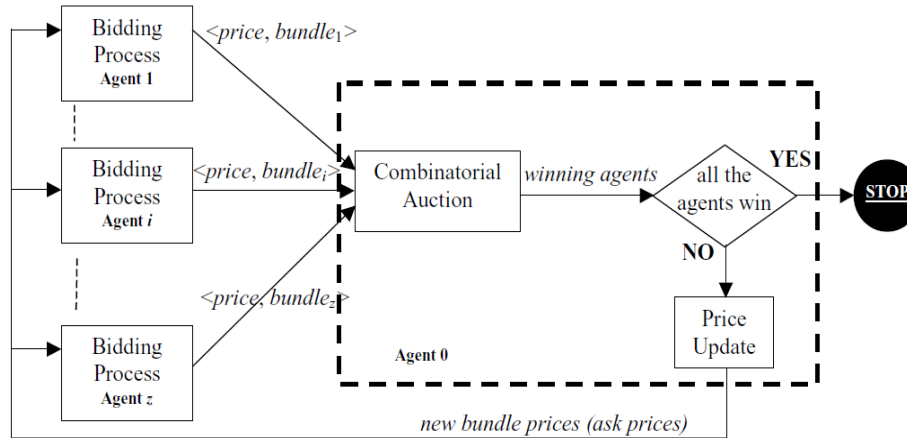


Figure 3.4 Multi-agent system functional schema (Confessore et al., 2007)

They proposed an iterative ascending price bundle combinatorial auction model. In this model, at each round of iteration, each project manager offers its bid including price and specific set of time slots i.e. bundle of goods, which he/she needs for the shared resource.

In this bidding problem, each project agent should solve a RCPSP. In order to do this, Confessore et al. (2007) adapted the well-known heuristic algorithm based on the parallel generation schema with the ‘latest finish time’ priority role which was originally proposed by Kolisch (1996), (see Section 3.2).

All the bids are collected by the auctioneer. The auctioneer seeks to maximize its selling revenue by solving a combinatorial auction problem which is known to be NP-hard. They proposed four different heuristic algorithms based on a relaxation (DPR) of a Dynamic Programming (DP) formulation of the combinatorial auction problem.

They have considered both precedence and resource constraints in the project network; however, they assumed that there is only one shared renewable resource

among projects with maximum capacity of one. Moreover, they only considered a single-mode resource constrained scheduling problem in bidding problem (see, Section 3.2.1 for more details). These assumptions are unrealistic in a real project environment.

The models proposed by both Lee et al. (2003) and Confessore et al. (2007) are based on modern electronic auctions for resource allocation and use simple heuristics for scheduling activities. In addition, according to their computational results their methods are suitable for small multi-project examples. Following their publications, a number of other researchers proposed the improvements in modelling and solution algorithms.

Homberger (2007) introduced a restart evolution strategy (RES) -a metaheuristic approach- that could find the solution for RCPSP centrally as well as a MAS that could solve DRCMPSP (solving the problem decentrally). The main objective of his research was to find a solution for large size problems. He proposed an evolution strategy combined with a restart model (multi-start approach) called RES. He applied RES for i) solving the RCPSP ii) solving DRCMPSP centrally and iii) Solving projects individually based on a decentralised approach i.e. the DRCMPSP.

In order to conduct the third approach above, he developed a MAS by defining two types of agents:

- i) Schedule Agents, similar to project manager agents introduced by Confessore et al. (2007). These agents are responsible for scheduling the project activities requiring the shared resources through conducting an iterative negotiation process.
- ii) A Mediator Agent which is in charge of generating alternative allocations and facilitating the coordination between Schedule Agents who evaluate the schedule of the projects' activities.

The negotiation process is comprised of two phases:

- i) Initialising phase where a start solution for the multi-project is calculated by allocating shared resources to each project by mediator and decentrally scheduling projects by Schedule Agent.

ii) Iterative improvement phase where the effort is made to reduce the average makespan of the projects by reallocating shared resources to them. The researcher ran simulations consisting of up to 20 projects with up to 120 activities per each project and then compared the results. For inputting instance data of DRCMPSP to RES, he used the super-network approach (see, Figure 3.1). He also inputted the data of each single project to RES individually and used the MAS to coordinate between the projects. Finally, he compared the results with each other. He concluded that “decentralised MAS approach is competitive with a central solution using the RES”. According to his findings, he designed a website called Multi-project Scheduling Problems Library (Hombberger, 2008). This website is currently used for other research works in this area. The researcher can solve the available problem instances in the website and compare their solutions. Although he considered more than one shared resource in project portfolio environment, an extension to the assumption used by Confessore et al. (2007), he did not take the **multi-mode** problem (see, Section 3.2.2) into consideration. Recently, Adhau et al. (2012) proposed a multi-agent system which he called a distributed multi-agent system using auctions based negotiation (DMAS/ABN). This method uses an auction-based negotiation for allocation of resources to projects. In order to achieve this they developed a MAS by defining 3 types of agents:

- i) Project Agents. The project agent represents a project and undertakes scheduling duties. Each Project Agent has its own scheduling functionality denoted as scheduler that encapsulates a local decision making algorithm. The PAs bid for the required global resources in the market.
- ii) Resource Agent. This represents the resource manager and owns and controls all global resources. It offers resources to the projects and keeps a record of the utilization of each of them.
- iii) Exchange Agent. This acts a coordinator, identifies conflict due to competition for global resources and uses the auction mechanism to resolve these conflicts. It also maintains the global clock and synchronizes the clocks of all other agents

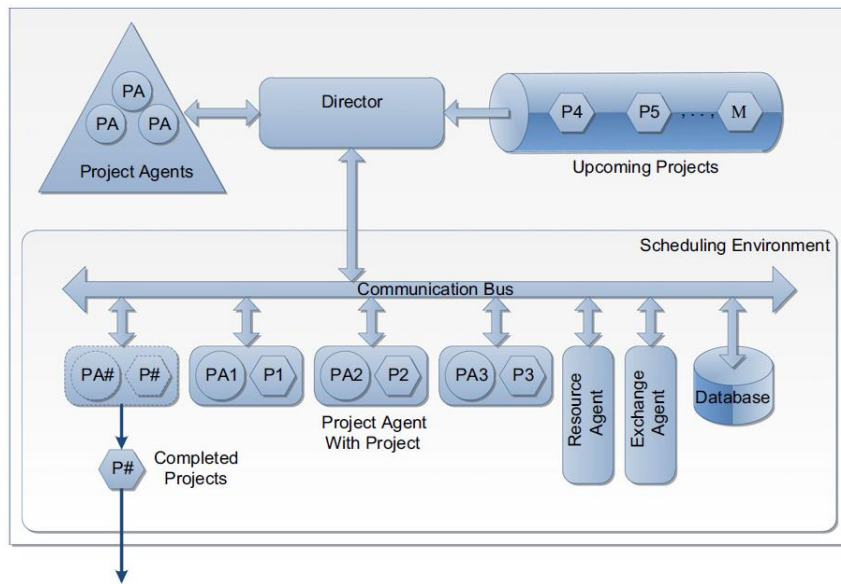


Figure 3.5 Multi-agent architecture of (Adhau et al., 2012) model

As it is shown in Figure 3.5, they also designed a “Director” in their architecture. The duties of the director are to generate project agents for each of the projects at its arrival, to initialise the resource agent and exchange agent and to control the system state by communicating with the exchange agent and the resource agent. The exchange agent plays the role of the auctioneer. It sells the current time slots to the bidders (projects). The base price is set by the global resource unit cost. Each project agent has differing needs of global resources; they compute the ideal time of their ideal local resources, and the cost of delay of the project beyond the project deadline along with the global resource unit cost. The auctioneer sorts and announces provisional winners and gives the chance for the losers to modify and resubmit their bids. Therefore, in an iterative auction process the current time slot of the available global resources is sold to the project agents. The exchange agent provisionally allocates global resources to the projects, in each iteration the project agent who is enhanced with a scheduler, computes and generates a feasible solution. Based on the obtained schedule, the project agent is able to compute the bid price in each iteration.

In order to obtain a feasible schedule, the project agent resolves a normal resource constrained scheduling problem (RCPSP). To do this it uses the heuristic priority roles and the parallel scheme. Adhau et al. tested their model on 140 DRCMPSP test instances generated by Homberger (2008), and evaluated results obtained for

average project delay (APD) and total makespan with the algorithms proposed by Homberger (2007) and an algorithm from Kurtulus & Davis (1982) (priority rule based heuristic, see Table 3.4). They concluded that their algorithm can solve large RCMPSP instances with any number of activities, resources and projects and can deal with the dynamic arrival of projects into the portfolio within a short computational time.

Despite its apparent competence in comparison with the other MAS models discussed so far, the model still does not take into account several real life factors. For example, in real word problems and particularly in the construction industry each project is concerned with a time-cost trade-off problem where each activity could be performed with different options/modes. The model proposed by the authors does not take this into account and hence it cannot currently be used for real life problems in the construction industry.

3.4.3 Decentralised hierarchical multi-project planning

In the recent study provided by Arauzo et al. (2010), a new model is proposed which adds further complexity. It adds the possibility of making the tactical decision i.e. “accepting or rejecting new projects” in auctions to the scheduling multi-project problem. They have added tactical decision-making approach over operative decisions like scheduling in traditional models. Indeed, this is the main contribution of their study which integrates two levels of hierarchical multi-project planning (see, Section 2.3). Figure 3.6 shows the architecture of the proposed model.

They introduced three types of agents in their model:

- i) Project manager agents, which play the role of bidder, participate in the auction process, and make contracts with resources for conducting activities with minimum cost.
- ii) Resource manager agents, which control resources and seek to maximize their incomes.
- iii) MAC agent (auctioneer), which is responsible for creating the project manager agents when new projects are added to the portfolio, monitoring the activities performed by the resources, and playing the role of an auctioneer based on a centralized nature.

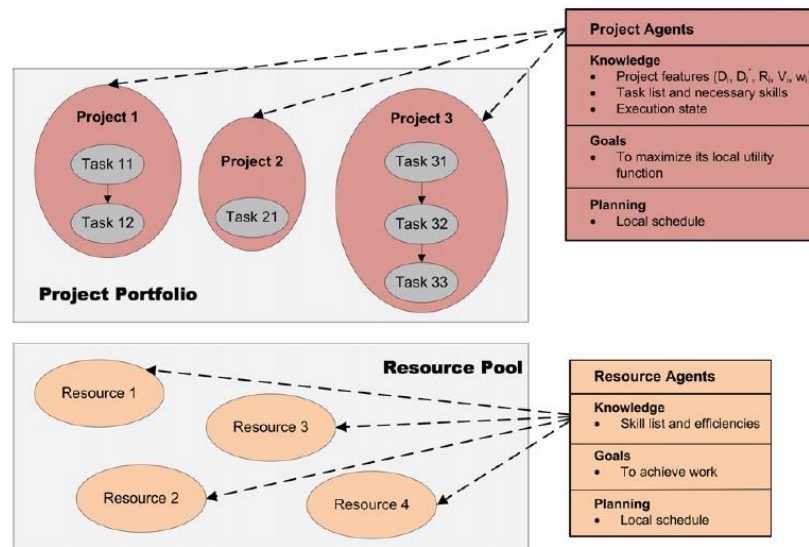


Figure 3.6 Project and resource manager agents (Araújo, Pajares, & Lopez-Paredes, 2010)

These agents interact with each other on two different levels:

- i) Auction interactions - where project manager agents make plans locally i.e. acceptance/rejection decision and generating local schedules
- ii) Contract interactions - where project's manager agents and resource manager agents make firm agreements regarding the use of time slots of resources.

MAC as an auctioneer initiates the auction procedure that allocates tasks to time slots and resources. In this procedure, it determines the price charged for resource time intervals. Its purpose is to reduce the resource conflicts and to maximize the resource revenue. For price adjustment in each round of bidding, a sub-gradient optimization algorithm is applied.

In addition to this project manager agents use a dynamic programming DP algorithm in order to select the set of time slots for conducting their pending activities whilst aiming to minimize their local cost. Selecting the best local schedule for each project depends on the prices of the resources determined by MAC.

In contrast with traditional approaches regarding project selection (see, Section 2.6), the decision about acceptance/rejection of a new project is made locally by its own project manager agent based on the following three conditions:

- i) The revenue obtained from the project does not cover the costs.

- ii) All possible combinations of time slots lead to schedules exceeding the delivery date i.e. the project could not be delivered on time.
- iii) The impact of the rest of the projects on the schedule is not acceptable.
i.e.:
 - a) If the new project is obliged to delay a contracted project beyond its delivery date.
 - b) If the inclusion of the new project increases the delay costs of the other projects more than the direct benefit obtained for the project.

The initial schedules have been generated locally by project manager agents through an auction process which was facilitated by an auctioneer (MAC) and makes firm agreements between projects and resource manager agents. Moreover, it can be noted that in their model they have not considered any local resources meaning that all of the resources are available in the category of “global resource.”

They proposed some new contributions to the literature including i) combining project selection with the resource scheduling and ii) considering variable time duration for each activity depending on the resources allocated. However, their research was limited due to several assumptions. This includes allocating only one resource to each task. Their model does also not consider the “task precedence conflicts” problem. This means that, the activities of any project should be executed sequentially in the order defined by number of activity per each project. The lack of inclusion of this in their model makes it unrealistic in complex multi-project environments.

3.5 Investigation on adopting a modelling approach

According to the extensive literature review conducted in this chapter and considering the requirements of the real world construction industry, it seems that there is a gap between theory and practise for multi project scheduling problem. In order to summaries the discussions made in this chapter, Table 3.5 highlights the advantage and disadvantages of the available models in the literature to facilitate the process of selecting the appropriate mathematical formulation, its corresponding solution algorithm and in general selecting a suitable modelling approach to address the requirements of the real world problem.

Table 3.5 Analysis of existing methods and adopting a modelling approach for multi-project planning

Row	Authors	Pareto front curve for each project	Generalised precedence constraints	Note
Centralised approaches				
1	Pritsker et al. (1969)	No	No	Modelling: Super-network Solution: Exact method for small size problems
2	Vercellis (1994)	No	No	Modelling: Super-network Solution: Exact method for small size problems
3	Gonçalves et al. (2008)	No	No	Modelling: Super-network Solution: GA
4	Kurtulus & Davis (1982) Kurtulus (1985)	No	No	Modelling : Individual network Solution: Priority rule models
5	Kumanan et al. (2006)	No But the projects modelled based on multi mode model.	No	Modelling : Individual network Solution: a GA for project prioritising and a heuristic for scheduling.
Decentralised approaches				
1	Lee et al. (2003)	No	No	Projects are modelled as single mode RCPSP. Solution algorithm is suitable for small size problems.
2	Confessore et al. (2007)	No	No	Projects are modelled as single mode RCPSP. They consider only one shared global resource.
3	Homberger (2007)	No	No	Projects are modelled as single mode RCPSP.
4	Adhau et al. (2012)	No.	No	Projects are modelled as multimode RCPSP. But still it does not consider time cost trade-off
5	Arauzo et al. (2010)	No. But the projects are modelled based on time-cost trade-off.	No	It does not consider the precedence constraints. They proposed a method for integration of project scheduling and project selection.

Moreover, although the decentralised multi project scheduling models discussed in the previous section attempt to address the distributed decision making environment, only a few of them cover the dynamic nature of the system. In addition, none of them address uncertainty in the context of project portfolio management.

This is why Hans (2001) claimed that “from a practical point of view, it is questionable whether it makes sense to solve such large problems to optimality, since information regarding resource availability and project characteristics are usually uncertain in the long term”. He concluded that “solving multi-project scheduling problems with a long planning horizon is more a mathematical

challenge rather than facing with a real world problem.” Therefore, Hans et al. (2007) in their Omega paper proposed a hierarchical multi-project planning framework looking at uncertainty in real world problems. They also proposed a positioning framework regarding uncertainty and interdependency between multi-projects and suggested how the best scheduling/ rescheduling problem should be adapted to accommodate the requirements of each position. These features will be discussed in details in the next chapter.

In brief, based on the above mentioned analyses, the author concluded that multi agent system architecture is a viable approach for decentralised multi project planning and can enable the designer to integrate several interrelated decision making processes together. It can be utilised for decentralised multi projects - one of the main characteristics of the construction industry. Negotiation and communication processes in MAS architectures facilitate autonomous agents to collaborate and coordinate together to achieve their goals. However, the literature review revealed that so far none of the studies addressed the real construction planning requirements and the devising of a new methodology is a valuable research line.

3.6 Summary

In this chapter, state of the art studies in single and multi-project scheduling were reviewed. Although centralised approaches are well studied, decentralised approaches are more relevant to the multi project planning in the construction industry. Multi agent technology and its applications for system modelling in decentralised multi project scheduling were discussed. Finally a summary of the gap analyses was tabulated to compare the methods. Although MAS architecture is a viable methodology for decentralised multi project scheduling, the available models are unable to satisfy the requirements of the practitioners in the real world construction industry. Therefore, in the next chapter, these issues including dynamics, uncertainty and complexity will be reviewed to understand how a practical model can be developed to address these requirements.

CHAPTER 4 DYNAMICS, UNCERTAINTY AND COMPLEXITY

4.1 Introduction

So far, a wide range of studies have been reviewed in order to understand the pros and cons of the different models and solution approaches for multi-project planning and scheduling. Although there is ample research including centralized and decentralised approaches for multi-project planning, only a little attention has been paid to the dynamic nature of the project portfolio environment. Moreover, the literature on uncertainty in multi-project version of the scheduling problem is virtually non-existent.

Project portfolio management is dynamic, uncertain and complex where frequent changes occur. Active projects are continuously reviewed and modified according to their progress. In addition, new projects can be introduced into the portfolio while some others are finished.

As discussed in the research methodology in Section 1.6.4, during the process of verification of the proposed model by the practitioners (see

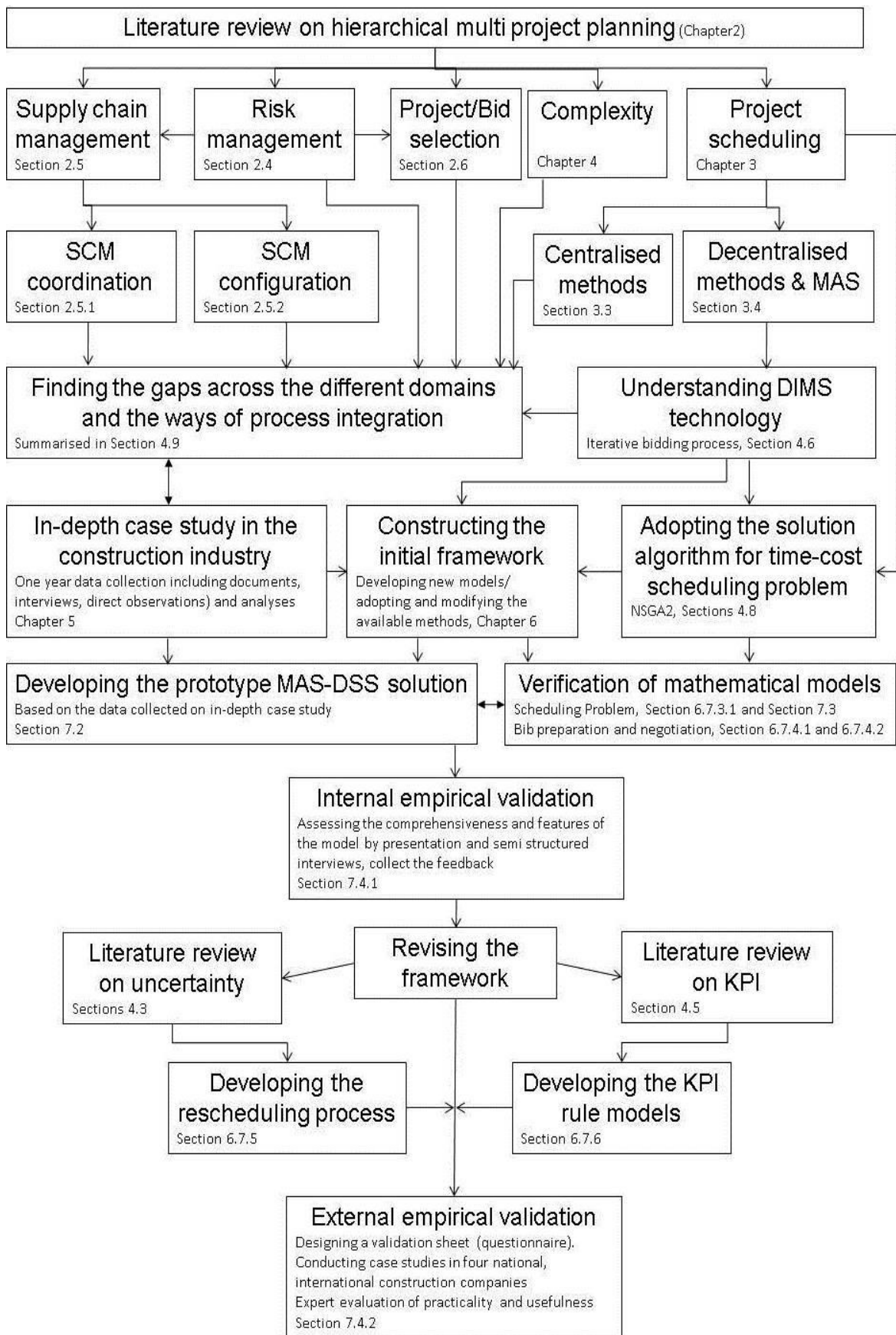


Figure 1.4), these aspects were discussed to shed light on ways of improving the

proposed initial framework. Before considering the practitioners' perceptions and ideas, the feedbacks and the insightful comments needed to be compared with the existing knowledge in the literature to identify the gap between theory and practice. Thus, as the last part of the literature review conducted in this study, in Sections 4.2 to 4.5 these aspects will be discussed and the main research papers reviewed to understand the dimensions of these issues and their effects on complexity. Later in the chapter in Section 4.6, DIMS as a methodology for tackling complexity will be illustrated and gap analyses conducted to identify how this methodology can be adopted to integrate the identified different decision making processes. The chapter will end with a summary of the adopted models and guidelines for constructing the new integrated framework for hierarchical multi project planning and supply chain management in the construction industry.

4.2 Dynamics

Most of the research reviewed so far was restricted to the static version of the multi-project scheduling problem. In the static version it is assumed that the decision for selecting and also scheduling the projects has to be made at time $t = 0$, the start time of period 1, and remains fixed until the end of the time horizon (time T).

With respect to the dynamic nature of the project portfolio planning, since most of the researchers assume that the environment is deterministic and number of projects is known at the beginning of a limited planning horizon, these models are not suitable for the real project portfolio context in which continuous management action is required.

Following a comprehensive literature review in the field of multi-project planning and scheduling, it appears that only a few research works consider the dynamic nature of the portfolio. Yang & Sum (1993) are the pioneers of dynamic multi-project scheduling (see Section 2.3). They consider the dynamic intervals of the projects and determine the performance of due date, resource allocation, project release and activity rules in multi-projects. To the best of the author's knowledge, Kao et al. (2006) is the only research group who proposed the resource constrained multiple project scheduling problem in a dynamic environment. They

adopted an event-driven approach based on reactive scheduling as depicted in Figure 4.1.

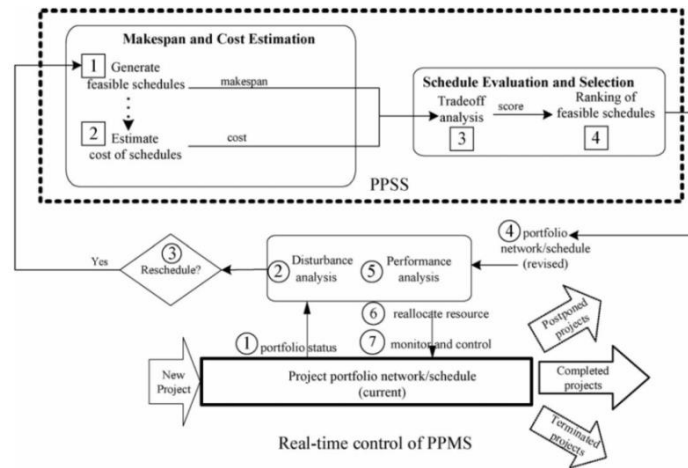


Figure 4.1 The event-driven procedure of project portfolio scheduling (Kao et al., 2006)

Kao et al. (2006) argued that because during execution of the projects there are some uncertainties, both scheduling and rescheduling should be accommodated in an integrated framework. They applied High Level Petri nets, Activity-Based Costing, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to generate feasible schedules, estimate their makespan and costs, and select the best compromise schedule sequentially. In their approach, they claimed once a significant event entered the portfolio in terms of urgency and seriousness then scheduling modifications must be done to accommodate this new event.

They also considered uncertainty and investigated its effect as an event that needs disturbance analysis and rescheduling in their proposed procedure. Although this procedure seems to be more realistic in comparison with the other studies, it is limited to the scheduling aspect. Project selection and supply chain configuration still need to be addressed in a novel framework and its incorporated procedures.

Looking carefully to the research work under the umbrella of multi agent system with respect to the decentralised multi-project scheduling problem also, one could realise that among the research mentioned in Sections 3.4.2 and 3.4.3, there are only two studies that claimed their approaches were suitable for dynamic situations, i.e. (Adhau et al., 2012) and (Araúzo et al., 2010). However, both of these research works assume that the projects were entered to the system in constant intervals which is far from reality.

With respect to the hierarchical multi-project planning (see Section 2.3), although Araúzo et al's (2010) research provides an integrated decision framework between project planning at the operational level and project selection at the tactical level, they suggest that their method should be extended to include more issues that occur in a real life situation such as precedence constraints, uncertainty, subcontracting etc.

In addition, considering the dynamic nature of the involved organisations in hierarchical multi-project planning, there appears to be a lack of knowledge regarding integration of supply chain design in strategic level of decision making and multi-project planning and scheduling in tactical and operational level of decision making in multi-project firms. In other words, although many scholars have proposed varieties of models for supporting management decision-making in the different levels of planning, proposing an integrated platform to support a practical linkage between levels has been neglected.

Looking at the current configuration and structure of the supply chain and its resources, one could realise that when a new project starts or when a project finishes the status of the resources is changed dynamically. Their status and attributes can be defined by their capacity, reliability and availability where they may become insolvent or change their attitude to keep working with the company as a member of the supply chain. Therefore, the structure of the resources should be investigated and reconfigured if required. This could be referred to the dynamic supply chain (Friesz et al., 2011). In other words, in project portfolios where resources and tasks dynamically change over time, it is necessary to design an integrated system for planning and managing complexity of the system. The situation would be more complex when uncertainty is also taken into consideration. This is a real challenge that none of the existing research works so far have accommodated.

4.3 Uncertainty

Uncertainty is one of the unavoidable parts of the real time project management environment. There are several reasons for uncertainty such as activities which may take more or less time than estimated, missing resources, late material

supplies, modified due dates, and new activities that may have to be incorporated. In addition, particularly in the construction industry, subcontractors or even general contractors (GC) may become insolvent and this causes disruption in collaborative environment of different subcontractors.

Regarding uncertainty there are two major streams of studies. One is focused on project planning and scheduling under uncertainty and the other covers risk management studies.

In this section, first the stream of project scheduling under uncertainty will be discussed then a literature review with regard to risk management particularly in the multi-project environment will be provided.

4.3.1 Uncertainty and single project scheduling

With respect to uncertainty in single project scheduling, a comprehensive survey of this research line can be found in studies conducted by Herroelen & Leus (2005) and Billaut et al. (2008). Different methods of schedule generation under uncertainty in single project environments are available. Generally, they are classified as proactive (robust) scheduling and reactive scheduling. Proactive (or robust) scheduling refers to generating a baseline schedule that tries to accommodate the anticipated uncertainty before the execution of the project. Proactive scheduling problems were classified as stochastic or fuzzy RCPS. This approach may use information about the particular variability characteristics (for example probability distributions for activity durations) Herroelen & Leus (2004a).

On the other hand, reactive scheduling refers to the schedule modifications that must be made during project execution. The purpose of reactive scheduling is to revise or to re-optimize the baseline schedule when an unexpected event happens rather than creating the baseline schedule as robust scheduling does. Basically most of the studies focused on “repairing” the baseline schedule (predictive reactive scheduling) to take into account the unexpected events that happen. There are two main strategies in reaction scheduling. Repair strategy is conducted in order to achieve a quick schedule consistency restoration. One the most popular approaches is the right shift rule (Herroelen & Leus, 2005). This rule will move forward in time all the activities that are affected by the schedule breakdown. This happens because of the precedence relations or because the activities were

performing by the resource(s) affected. Alternatively, full rescheduling strategy refers to a full scheduling pass of that part of the project that remains to be executed at the time the reaction is initiated and may use any deterministic performance measure, such as the new project total cost (Herroelen & Leus, 2005).

In this context predictive-reactive scheduling refers to integrating the proactive scheduling problem where for instance a stochastic RCPSP generates a robust baseline schedule (i.e. it incorporates safety time to absorb anticipated disruption) and a reactive procedure that is raised when a schedule breaking comes up during project execution (Vonder et al., 2007).

Looking at the literature, it appears that reactive scheduling needs to be studied for the time/cost trade-off problem particularly in the context of the construction industry.

4.3.2 Uncertainty and multi-project scheduling

Apart from research reviewed with respect to uncertainty in single project environment, Hans et al. (2007) analysed the multi-project environment and developed a hierarchical planning framework (see Section 2.3). This framework is coupled with a positioning framework based on two aspects, variability and interdependency between projects running simultaneously at the enterprises. Variability is taken to mean the same as uncertainty in this context. The positioning framework is presented in Table 4.1.

An on-site maintenance project that is performed on a preventive basis would be referred to as “LL”, low uncertainty/variability and low dependency between projects.

Table 4.1 Positioning framework for multi-project organisations (Hans et al., 2007)

Dependency	LOW	→	HIGH
Variability			
LOW	<i>LL</i>		<i>LH</i>
↓			
HIGH	<i>HL</i>		<i>HH</i>

“LH” describes the make-to-order job shop environment, where uncertainty is relatively low but different orders/products use a common pool of resources.

“HL” reflects the situation where projects are less dependent on each other and their resource pools are not overlapping to a high degree, however the variability of the environment is relatively high. They advocated that construction projects would be good examples of this kind of organisations because “Such projects are usually subject to large environmental uncertainties such as weather conditions and uncertain or frequently changing project specifications” (Hans et al., 2007). Since the allocated resources are often dedicated to a particular project with a considerable size, the interaction with the resources of other projects is minimal. Finally, “HH” is referred to as Engineering-to-Order organisations where every single project is completely new so it has lots of uncertainty even in design phases. In addition, interdependency between projects is high when an expert engineer is needed to design several products and time is the main barrier. They linked the positioning framework to the hierarchical multi-project framework (that has been discussed in detail in Chapter 2) and argued that in each position different hierarchical approaches should be implemented. They proposed their positioning framework as illustrated in Table 4.1 which can be applied at each level of the hierarchy. It seems that this positioning framework is in line with another positioning framework previously proposed by (Herroelen & Leus, 2004) as can be seen in Table 4.2.

Table 4.2 Different approaches to the (multi-)project scheduling problem (Herroelen & Leus, 2004a)

	<i>totally dependent</i>	<i>rather dependent</i>	<i>rather independent</i>	<i>totally independent</i>
<i>low variability</i>	7 stable plan; satisficing	5 stable drum; efficient remainder	3 efficient drum; efficient remainder	1 deterministic
<i>high variability</i>	8 process mgmt.; rough plan with sufficient slack	6 stable plan with queuing	4 stable drum; dispatch or predictive-reactive	2 dispatch or predictive- reactive

For selecting the appropriate project scheduling based on this positioning framework Herroelen & Leus (2004a) also claimed that a generic framework and methodology for project planning and scheduling in multi-project organisations are not appropriate practices. They also suggested several scheduling/rescheduling

methods for each position. However, the proper method should be investigated in its context and may be modified based on industry situations. Therefore, in this research the construction industry was investigated through in-depth case study to understand the requirements of the appropriate rescheduling model. This will be discussed in Chapter 6.

4.4 Uncertainty and complexity in construction project portfolio management

As discussed in Chapter 1, complexity is an unavoidable characteristic of project portfolio management. Sanchez et al. (2009) categorised four sources of complexity in project portfolio: “(1) the resources; (2) the technology or knowledge used or generated; (3) the functionality of the product developed; and (4) the market which represents the strategic relation between the organisation and its environment”. They believe uncertainty is the outcome of interaction between these sources. In order to achieve the project, program, or portfolio these sources should be analysed and controlled. They emphasise the non-linearity of the complex systems. Nonlinearity refers to the fact that the outcome of the system in response to any small changes in the environment is hard to predict. According to Sanchez et al., since events and consequences in the multi-project environment are non-linearly related, further research studies are needed to provide tools and techniques to accommodate this non-linearity.

Further to these characteristics, it seems that most of the studies in construction project management are focused on single project management. As it was discussed, using work breakdown techniques along with critical path analysis and RCPSP provides frameworks to control projects and deliver predefined goals based on quantitative measures, the “hard paradigm” (Aritua et al., 2009), that are not suitable to accommodate uncertainty in construction portfolio management. Even most popular Bodies of Knowledge i.e. (PMI, 2013) and (APM, 2012) that have been implemented in the construction sector are also generally focused on achieving single project objectives (Aritua et al., 2009).

In a study by Blismass et al. (2004) it was revealed that although most of the construction companies have several projects simultaneously, each of them is managed and controlled individually with single project planning methods.

However, it seems that the paradigm of project management is changing gradually from hard to soft. In contrast with the hard paradigm whose objectives could be defined clearly by quantitative or by a mixture of qualitative and quantitative measures, there is a growing acceptance of the soft paradigm in the project management community (Pollack, 2007). As the soft paradigm could address the ill-defined objectives and also it focuses on “contextual relevance” rather than objectivity, it could well accommodate the requirements of the multi-project management.

Aritua et al. (2009) argue that project management can benefit from the study of behaviour of complex dynamical systems in different disciplines which tends to provide them with new insights. Using complexity theory provides a more holistic view to rework previous hard approaches.

Complexity theory could facilitate the understanding of the real world and its phenomena. It has been studied in markets, ant colonies, traffic systems, urban planning, airline networks, seismology, and virus research among others. Complexity theory could be a good approach to deal with uncertainties in construction multi-project environments.

Regarding complexity theory, Aritua et al. (2009) highlighted six components for complex adaptive systems including “Inter-relationships, Adaptability, Self-organisation, Emergence, Feedback, Non-linearity”.

They illustrated these characteristics by means of a graph as depicted in Figure 4.2.

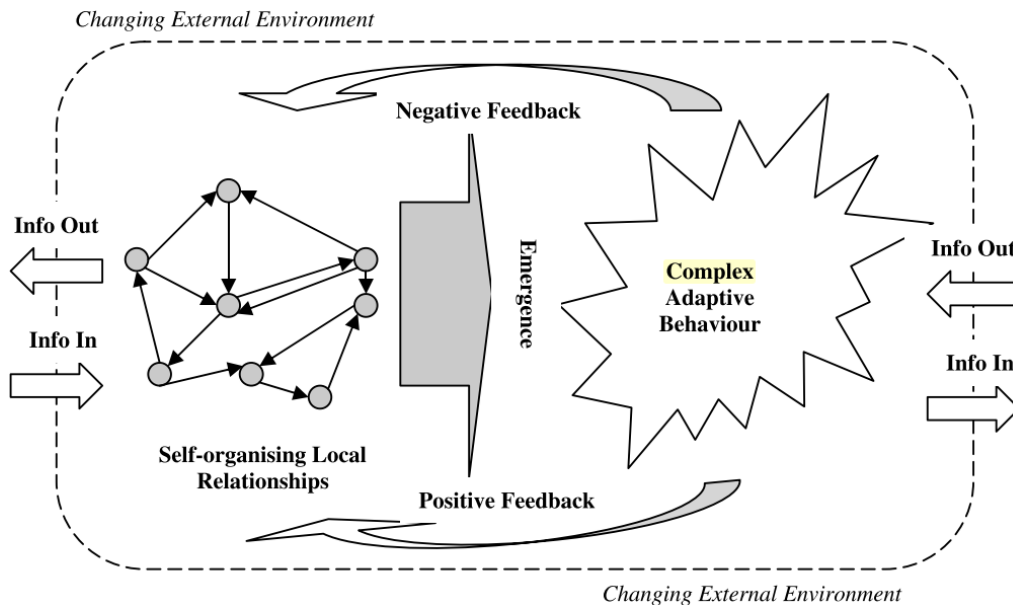


Figure 4.2 Complex adaptive behaviour (Aritua et al., 2009)

This graph shows how complex adaptive behaviour could emerge from a single project in interdependency with other projects and also its environment. As shown in Figure 4.2, being influenced by positive and negative feedback from external environment, the system would be then able to make the necessary changes in the relationships between projects so that “the complex multi-project environment adapts”.

One could ask why programme/portfolio risks are not equivalent to the sum of individual projects risks. Aritua et al. (2009) claimed that rather than managing single project individually, the enterprise could take more benefits if it managed a bundle of projects where different types of feedback (negative or positive) should influence future decisions of the portfolio.

Aritua et al. (2009) claimed that using complexity theory “project managers must be allowed to react - in independently and in a self-organized ways - to developments in individual single projects”. They advocated that the programme and portfolio managers should change their practices and allow the project managers to control and model details of individual projects. Therefore, the portfolio manager should make a balance between the levels of trust they place in their project managers so that project managers could have more flexibility in making their decisions independently. And to that end, the portfolio manager should merely control their project managers’ performance rather than interfering with their decisions.

Considering complexity theory as new approach for understanding multi-project management construction industry, Aritua et al. (2009) call for the use of the theory as the basis of case study analysis concurrently with the traditional methods of single project studies.

Finally, with respect to uncertainty, Atkinson et al. (2006) summarised all of the discussions that took place during meetings of the UK EPSRC funded Network on Rethinking Project Management over the period 2004–2006 to find out the general views of both scholars and practitioners on uncertainty. They concluded that organisations that have efficient and effective systems for coordination and control, environmental scanning, and organisation learning are able to better manage uncertainty and complexity.

Atkinson et al. claim that even in those organisations where data on past performance is available, receiving this sort of feedback from past projects as a required input for planning the new projects is a major challenge for project planning and management. They found that organisational culture, time pressures and the attitudes and behaviours of project management personnel are the main factors that contribute to this failure. In addition, by reviewing all of the discussions made within these two years, they noted that “ ‘Lessons learned’ is a popular term in the project management literature and amongst practitioners, yet it often masks payment of lip service only to the idea of learning from experience. The capture and re-use of learning from one project to another is generally accepted as something that should be done but it often goes no further than capture. It is often associated with post project reviews where learning has significant potential to reduce uncertainty” Atkinson et al. (2006).

Since the construction industry is fragmented and the projects are geographically dispersed, it is hard to share the knowledge gained from a particular project with other managers. Thus, mistakes can be easily repeated by the other project managers. It seems that for managing the uncertainty and complexity of project portfolios in the construction industry, there is a need to construct techniques and to develop new tools to capture the lessons learnt from previous projects.

In this context, the performance of the project management can be measured and compared in different sites to address the strength and weakness of each project

manager and its associated supply chain. This can lead to make decisions for improving the entire system. In the next section key performance indicators (KPI) in general and in the construction industry in particular will be discussed to highlight how a complex system can take advantage of feedback systems for continuous improvement.

4.5 Key Performance Indicators

Following the discussion at the end of previous section, project portfolio management needs to measure the projects' performances managed by several individual project managers. It would be a logical reasoning between using the lesson learned from the past project and the project performances expected in future projects. If an enterprise would be able to capture the project managers' experiences in projects, the knowledge and experience sharing can lead to improvements across the portfolio resulting in higher key performance indicators.

Fortunately, performance measurement as a concrete methodology for enterprise strategic management is studied over a long period. For instance, one could refer to (Folan & Browne, 2005) for a comprehensive survey. Particularly, there are a number of research works with regard to performance management in the field of construction industry (Chan & Chan, 2004), (Yang et al., 2010), (Presley & Meade, 2010), (Horta et al., 2012).

There are also a number of research works in the field of performance measurement that particularly were conducted in construction industry in the UK (Lema & Price, 1995), (Bassioni et al., 2004), (Bassioni et al., 2005), (Tennant & Langford, 2008), (Deng et al., 2012). For instance, Lema & Price, (1995) examined the applicability of benchmarking in construction industry as a methodology toward competitive advantages. They advocated that continuous improvement is a key element from total quality management (TQM) concept that has been widely used in manufacturing industry. They suggested the development of framework and methodology in order to adapt benchmarking for continuous improvement in CI. Tennant and Langford (2008) conducted a study considering three market leader companies and collected data for seven KPIs with regards to a number of projects

across these companies in order to drive the norm within the industry. Table 4.3 shows the results of their conducted case study.

Table 4.3 Summary of the case studies (Tennant & Langford, 2008) and KPIs comparison

Key Performance Indicator	Project B/1	Project B/2	Project B/3	Project B/4	Project B/5	Project C/1	Project C/2	Project C/3	Project D/1	Project D/2	Project D/3	Project D/4	Project D/5	KPI Mean
Predictability Construction - Cost	75	75	27	95	70	75	22	26	16	35	20	75	20	49
Predictability Construction - Time	25	39	26	19	60	60	34	33	28	16	27	60	34	35
Client Satisfaction - Service	55	10	10	27	55	85	100	55	55	55	100	100	100	62
Client Satisfaction - Product	55	55	8	2	20	85	85	8	21	0	100	100	85	48
Employee Satisfaction	61	67	45	46	82	73	60	45	45	85	77	75	62	63
Hours Worked (per week)	22	14	18	20	38	22	26	12	17	17	23	17	24	21
Training Days (per year)	88	75	72	89	94	92	89	95	95	86	91	93	88	88
Project KPI Mean	54	48	29	43	60	70	59	39	40	42	63	74	59	

Furthermore, there are some studies pertaining to system design and system architecture for supply chain performance measurement, (Folan et al., 2006), (Saiz et al.,2010). In the latter, they introduced a performance management framework for collaborating SMEs by proposing information architecture. This framework is composed of a methodology, information architecture and a technological solution. They showed that the proposed framework will enable SMEs to manage their performances in order to “improve their competitive capability and network visibility”.

Fortunately, in the UK there is a particular website entitle “KPI Engine and Zone” for “Construction Industry key performance indicators” that has been established based on Sir John Egan's report ‘Rethinking Construction’ (Egan, 1998) developed by CCI (Centre for Construction Innovation, 2013). CCI is responsible for providing required guidelines, information collection and KPI calculation. KPI Engine & Zone is a system framework that supports construction industry to benchmark their activities.

Owing to the technological improvements in measuring KPIs in the construction industry, it would be a great opportunity to utilise the available architecture in KPI Engine & Zone in order to integrate tactical and strategic decisions in a single unique platform as discussed by Aritua et al. (2009). It can lead to capturing positive and negative feedback as shown in Figure 4.2. Thus it can assist in managing the complexity and help the adaptability of the system.

4.6 DIMS technology, a lesson from manufacturing systems for modelling project portfolio management

Dynamically integrated manufacturing systems (DIMS) is a methodology for modelling and controlling manufacturing systems. It has been developed over a decade in Exeter Manufacturing Enterprise Centre (XMEC) to address problems such as production planning, process planning, system restructuring and supply chain configuration. It is capable of doing this in a dynamic manner in order to cope with uncertain market environments for make-to-stock products (Goh & Zhang, 2003), (Lim & Zhang, 2003), (Lim & Zhang, 2004), (Zhang et al., 2006), (Zhang et al., 2007), (Akanle & Zhang, 2008), (Anosike & Zhang, 2009), (Lim et al., 2009). In DIMS a hierarchical multi-agent framework namely HAAN (Hierarchical Autonomous Agent Network) is proposed to model complex manufacturing systems, their structures, and also constraints. It is able to generate an optimal solution for product scheduling (Zhang et al., 2007), and even supply chain configuration for order fulfilments (Akanle & Zhang, 2008).

Owing to the DIMS capabilities for system integration across different decision making levels, this methodology seems to be a viable approach for devising a system framework for multi project planning and supply chain management. Therefore in the following sections, DIMS will be shortly introduced and then critically analysed to understand how this methodology can be utilised and adopted for multi project planning in the construction industry.

4.6.1 DIMS concept

DIMS is an integrated decision making platform for manufacturing systems. The aim of this platform is to raise the responsiveness of manufacturing systems to

changes in the business environment. There are five decision options in DIMS including scheduling, planning, configuration, restructuring and system adaptation options.

The platform is implemented by a multi-layer hierarchical agent-based modelling and simulation architecture for modelling complex heterogeneous systems. It models the system structure as well as product work breakdown structure. The agent-based architecture facilitates the implementation and the execution of a hierarchical and optimally controlled agent-based bidding process including a method for identifying, simulating and evaluating system restructuring options in order to accommodate changes in the business environment (Zhang et al., 2007).

4.6.2 Combinatorial optimization through Iterative Bidding Process

For scheduling of each job/order in DIMS, a coordinated iterative bidding process, inspired by the negotiation process between sellers and buyers has been proposed and tested in XMEC. The agent coordination algorithm operates iteratively under the control of a genetic algorithm in order to minimise the cost of the order while controlling its due date. This process provides an optimal combination of resources for an order by implementing several bidding iterations (see (Zhang et al., 2007) for the details of the procedure).

The iterative bidding process is the core of DIMS concepts and has been implemented by all the researchers who work in DIMS strand. As a good example, Akanle & Zhang (2008) utilized the procedure to solve a deterministic time-cost combinatorial problem where eligible resources bid for the nodes of a supply network. Each order was modelled as a TCTP-D problem (see Section 3.2.2.1) where iterative bidding process was used to find the optimal combination of the different resources to fulfil the order. They implemented the procedure in a supply network with 13 nodes each of which had several eligible resources that offer time-cost options. The precedence relationship between the nodes is similar to a project network with zero time-lag. The total resource combination that was tackled with the iterative bidding process was 24,576. They showed that the iterative bidding process is able to provide near optimal solutions for supply chain configuration. Following this, they considered that there is a series of orders that should be

fulfilled by the network. They ran iterative bidding process for each order to find out different solutions for each. Then, they used probability clustering procedures (using a Chain Configurator Agent) to find the global configuration as it will be discussed in the next section.

4.6.3 Configuration procedure

After the iterative bidding process has determined the required optimal resource combination to fulfil each order, the system starts to detect frequently used resource combinations for a series of orders. These combinations are then placed in a rank-ordered list from high to low frequencies after which the clustering procedure can be started.

Probability clustering is developed based on Bayesian Theory. The rule states that given a hypothesis H and evidence E supporting the hypothesis, the probability of the hypotheses occurring given the evidence is:

$$\Pr[H|E]= \Pr[E|H] \cdot \Pr[H] / \Pr[E] \quad (4.1)$$

where $\Pr[E|H]$ is the probability of occurrence of the evidence given that the hypothesis is true, $\Pr[E]$ is the unconditional probability of occurrence of the evidence, and $\Pr[H]$ is the prior probability that the hypothesis is true assuming that evidence E is not provided (Zhang et al., 2007).

After conducting probability clustering, qualitative analysis that evaluates the suppliers' performances is undertaken. This qualitative evaluation covers the quality, reliability of delivery, responsiveness to changes etc. of the suppliers. This analysis helps the manufacturer to set for instance an acceptable predefined reliability of the suppliers. It removes those suppliers from the outcomes of the clustering process whose reliability is less than the level specified. In these cases, the supply chain configuration could guarantee a higher level of reliability of the total performance of the system with a slight increase of the total supply chain cost. The most frequently used structure is then found, evaluated and clustered to form the new configuration of the system (Anosike & Zhang, 2006), (Akanle & Zhang, 2008).

Although the probability clustering approach seems to be a promising method, it seems appropriate that the qualitative analyses should be undertaken prior to the quantitative analyses. In real world cases, manufacturers often pre-evaluate

suppliers. If their performances are acceptable and they cover the minimum acceptable criteria of the manufacturers then more quantitative analyses will be conducted on them. If not then they will be removed from the valid list and therefore, bidding operations and negotiations will never be undertaken with them.

4.7 Lessons learned from DIMS and its required improvements

As it is discussed in the previous section, DIMS is a novel approach for managing manufacturing systems. It utilises agent based technology in order to deal with complex systems.

It provides a generic method for optimising manufacturing systems accommodating both process planning and production planning simultaneously in an integrated and dynamic manner.

The scope of DIMS technology that has been designed and tested in manufacturing systems is limited to deterministic production planning. However, it has been shown that iterative bidding process could be modified to accommodate uncertainty in delivery time (Akanle, 2008). In the area of uncertainty there are still more factors that could be taken into account. These include; a stochastic demand model where the demands of the products are based on a probability function and the breakdown of machines. Furthermore, the feedback of the performance of the system could be taken into consideration. The system performance in demand response could potentially result in higher demand rate in future and vice versa while in DIMS product demand rates is considered to be constant and also the interval between them is considered deterministic which is far from real world manufacturing systems.

The other issue that needs to be addressed is in hierarchical agent bidding mechanism, DIMS initially considers sequential operations in each component of product order and allocates the resources to the operations sequentially. However, when the resources in the current system configuration are unable to carry out all the operations required, system constraints are gradually relaxed to allow other available capacities in other work cells to be utilised. At the last step of this relaxation, the algorithm is faced with a pool of resources that should be allocated

to different operations. Finally components should be assembled to produce the final products (He, 2011). This is shown in Figure 4.3.

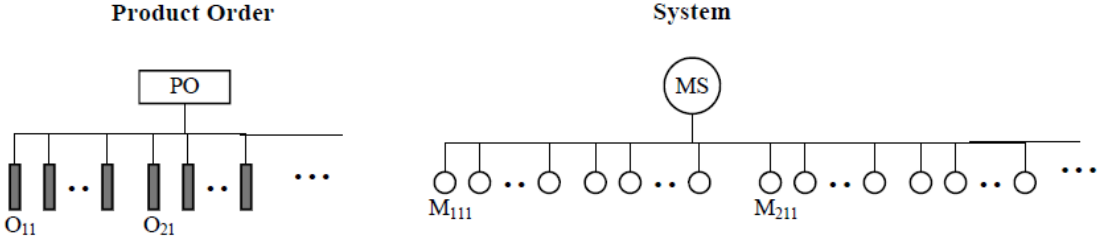


Figure 4.3 The relaxation of structural constraints in resource regrouping (step 4) (He, 2011)

This resource allocation is similar to the parallel job scheduling in a simple typical project network (see Section 3.2 , and Figure 4.4).

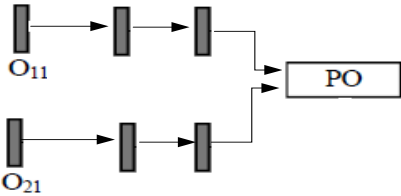


Figure 4.4 Parallel job scheduling

As the levels of subassemblies in products are increased, the metaphor project network becomes more complex and more parallel operations could be carried out simultaneously. This means that iterative bidding process that only handles the operations sequentially would no longer work. Where jobs could practically be operated in two or more parallel chains of operations and there is only one machine capable undertaking both operations O11 and O12, allocating the machine should be investigated to find out which priority role could provide better results (minimum makespan or cost or resource utilisation).

As it discussed in Section 3.2, for resolving this shortcoming a large number of research works are available (Demeulemeester & Herroelen, 2002). This is beyond the scope of the present research (a classification of the models provided in Section 3.2.), however, it could be potentially useful research for promoting DIMS concepts.

Finally, looking at DIMS optimisation engine, one could realise that iterative bidding process plays the main role as an optimisation tool.

The comparison between optimisation of time-cost combinatorial problem in DIMS stream through iterative bidding process and time-cost problem mentioned in

Section 03.2.2.1 reveals that implementing multi objective optimisation that is frequently used by scholars might be another viable opportunity to improve DIMS. It should be noted that, although the iterative bidding process controls time and minimises the cost, it does not present any trade-off curve through several iterations. It is therefore still classified as a single objective optimisation method.

In contrast with single objective optimization where the solution is a single optimal solution, Time-Cost optimization is a multi-objective problem. Dealing with this sort of problem, one could find a set of solutions known as the Pareto-front solutions (Feng et al., 1997). The analyst should attempt to find as many Pareto-optimal solutions as possible. Since evolutionary algorithms (EAs), such as GA, work with a population of solutions, a simple EA can be extended to maintain a diverse set of solutions. Multi objective evolutionary algorithms (MOEAs) have been proposed as early as 2000. In comparison with other MOEAs such as Pareto-archived evolution strategy (PAES) (Knowles & Corne, 1999) and strength-Pareto EA (SPEA) (Zitzler, 1999), the Fast and Elitist Genetic Algorithm namely NSGA2 (Deb et al., 2002) is one of the most interesting and effective methods which is widely discussed in the literature (Ghoddousi et al., 2013). A brief introduction of NSGA2 is presented in appendix A.

In the next section a test case will be set to compare iterative bidding process with NSGA2 to identify the strengths and weaknesses of the two methods and to select which one is more suitable for the remainder of the research.

4.8 Comparing NSGA2 and DIMS optimisation engine

In order to understand exactly how NSGA2 works and to compare its competency with the iterative bidding process a test study is conducted.

Since the test case that is used by Akanle & Zhang (2008), has more nodes than other test cases in DIMS and includes a zero time lag precedence relationship network rather than a simple 3 or 4 sequential operations, it is selected to compare the competence of iterative bidding process with NSGA2. The aim of this is to compare the results obtained from NSGA2 with the Iterative Bidding Process that has been used for more than a decade in XMEC.

4.8.1 Test case of Iterative bidding process

The test case is a combinatorial problem in the field of Supply Chain Configuration where the time-cost problem is solved to find the best combination of the selected suppliers for fulfilling each particular customer order. The data is shown in Table 4.4.

Table 4.4 Resource options for computers (Akanle & Zhang, 2008)

Stage	Node	Components/process description	Option	Lead-time	Cost (\$)	
1	1	Parts w/8-week LT	1	40	130.00	
			2	20	133.25	
			3	10	134.91	
			4	0	136.59	
	2	Parts w/4-week LT	1	20	200.00	
			2	10	202.50	
			3	0	205.30	
	3	Parts w/2-week LT	1	10	155.00	
			2	0	156.93	
	4	Parts on consignment	1	0	200.00	
	2	5	Circuit board assembly	1	20	120.00
				2	5	150.00
6		LCD display	1	60	300.00	
			2	5	350.00	
7		Miscellaneous components	1	30	200.00	
8		Metal housing	1	70	225.00	
			2	30	240.00	
9		Battery	1	60	40.00	
			2	20	45.00	
3		10	Laptop assembly	1	5	120.00
	2			2	132.00	
	11	CD-RW drive	1	40	30.00	
			2	5	35.00	
	12	DVD drive	1	40	15.00	
			2	5	16.50	
4	13	CD-RW assembly	1	1	30.00	
	14	DVD assembly	1	1	30.00	
5	15	US demand-CD-RW assembly	1	5	12.00	
			2	1	20.00	
	16	Europe demand-CD-RW assembly	1	15	15.00	
			2	2	30.00	
	17	US demand-DVD assembly	1	5	12.00	
2			1	20.00		

In addition the relationship between different stages in a supply chain is presented in Figure 4.5.

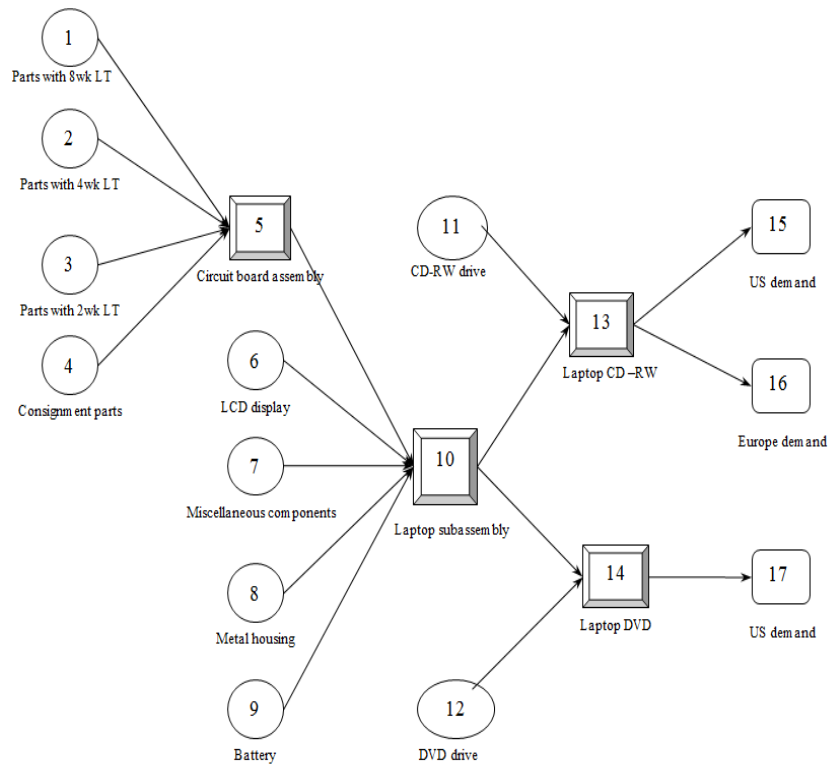


Figure 4.5 Required parts/operations for satisfying laptop orders (Akanle & Zhang, 2008).

In order to keep things concise, one of the products, DVD-US, was selected and the results obtained from running the iterative bidding process 9 times. The results of these runs are shown in Table 4.5.

As Akanle & Zhang (2008) claimed, the optimal solution is (68, 1781). They obtained this result twice in orders no 21 and 22.

Table 4.5 Solution obtained from Iterative bidding process (Akanle & Zhang, 2008)

Orders		Parts/Operations at nodes of supply chain network											Optimal combination			
		1	2	3	4	5	6	7	8	9	10	12	14	17	Cost (\$)	Lead-time (Days)
3	DVD-US	4	3	2	1	1	2	1	2	2	1	1	1	1	1839	42
9	DVD-US	4	3	2	1	1	2	1	2	2	1	1	1	1	1839	42
10	DVD-US	4	3	2	1	1	2	1	2	2	1	1	1	1	1839	42
12	DVD-US	4	3	2	1	1	2	1	2	2	1	1	1	1	1831	46
18	DVD-US	2	1	1	1	1	2	1	2	2	1	1	1	1	1831	46
21	DVD-US	1	3	2	1	1	1	1	2	1	2	1	1	1	1781	68
22	DVD-US	1	3	2	1	1	1	1	2	2	1	2	1	1	1781	68
24	DVD-US	1	3	2	1	1	1	1	2	2	1	2	1	1	1776	71
29	DVD-US	2	1	2	1	1	1	1	2	2	1	1	1	1	1772	71

4.8.2 Setting up the NSGA2

In order to run the algorithm, some definitions and preparations are required. The chromosome should properly be encoded and population size needs to be decided. In addition, thought needs to be given to the values of the crossover and mutator operators. In this subsection, a description is given to show how NSGA2 can be set up for solving the given test case while the two algorithms are compared.

4.8.2.1 Chromosome

In iterative bidding processes (Akanle & Zhang, 2008), a chromosome is represented by a vector composed of a full set of virtual prices and minimum virtual profits. In addition, the number of genes in a chromosome corresponds to the sum of the number of operations contained in the order and the number of resources available in the supply chain. The length of the vector is therefore relatively long. In contrast, in the present study and similar to (Feng et al., 1997) the chromosomes were defined in such a way that it represents the possibility of allocating different eligible resources to each node. A k-ary encoding was used in which a candidate solution is just a list of L numbers, each of which can be anything from 1 to k. The genes were defined as available resource options for performing a particular stage of the supply chain. The representation for 12 node in the supply chain and 1,2,3 or 4 possible resource, would be a 4-ary encoding of length $L=12$.

4.8.2.2 Population size

In this study, population sizes similar to those used by Akanle & Zhang (2008). First, the offspring population is created by using the parent population to generate a new population size of 200. The two populations are combined together to form a population of size of 400.

Then a non-dominated sorting is used to classify the entire population. Following this, the new population is filled by solutions of different fronts, one at a time. The filling starts with the best non-dominated front and continues with solutions from other fronts until a population size of 200 is reached.

4.8.2.3 Crossover

Crossover takes two individual solutions and uses random point(s) to cut the chromosome in two segments, a 'head' and a 'tail' segment (Goldberg, 1989). The tail segments are swapped over to produce two new chromosomes. Usually, crossover is not applied to all pairs of chromosomes, but has a likelihood of being applied typically between 0.6 and 1.0.

There are three crossover operators including simple one point, simple multi points and uniform random. These methods aim to share information between individuals and to create entirely new solutions which have some of the attributes of their parents. The two offspring are created by crossing over two parents. These new children are often better solutions than either of their parents however they could occasionally be worse.

In this test case study, a simple one point crossover operator was used and the crossover rate was set to 0.8.

4.8.2.4 Mutator

After the possible solutions have undergone crossover, mutation is applied. Mutation focuses on each particular child instead of pairs. It randomly changes a gene within its acceptable boundary to create a new chromosome. This operator is typically applied in a low percent of the population size and support the algorithm to escape from local optima. In this test mutation was considered in k-ary encoding. In order to do this the procedure chooses a gene at random and changes it to a random new value within its range. The mutation rate is set at 0.1.

4.8.3 Comparing the results and conclusion

After the required parameters had been set, the NSGA2 was run and results were obtained. These were compared with the previous study. In Table 4.6 the solutions obtained by NSGA2 is presented.

In Figure 4.6, the iterative bidding process for one of the orders for DVD-US is presented. It shows that after 25th generation the minimum cost was obtained and no improvement was observed until the end of the generations (30th run). This minimum cost has been obtained after undertaking 9 different runs each of which

had 30 generations. Figure 4.7 shows the Pareto-front curve that was obtained by a single run of the NSGA2.

Table 4.6 Solutions by implementing NSGA2 after one run with 30 generations

Solutions	Node Numbers (Genes)													total time	total cost
	1	2	3	4	5	6	7	8	9	10	12	14	17		
1	3	2	1	1	1	2	1	2	2	2	2	1	2	34	1846
2	3	2	1	1	1	2	1	2	2	1	2	1	2	37	1834
3	3	2	1	1	1	2	1	2	2	1	2	1	1	41	1826
4	3	2	1	1	1	2	1	2	2	1	1	1	1	46	1824
5	2	1	1	1	1	2	1	2	2	1	1	1	1	51	1820
6	1	1	1	1	1	1	1	2	1	2	1	1	2	64	1782
7	1	1	1	1	1	1	1	2	1	1	1	1	2	67	1770
8	1	1	1	1	1	1	1	2	1	1	1	1	1	71	1762
9	1	1	1	1	1	1	1	1	1	1	1	1	2	77	1755
10	1	1	1	1	1	1	1	1	1	1	1	1	1	81	1747

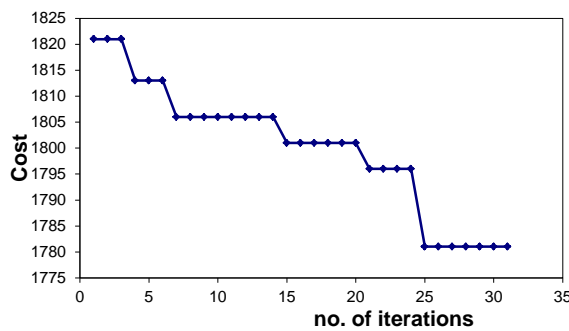


Figure 4.6 Iterative bidding process for order 21

(Akanle & Zhang, 2008)

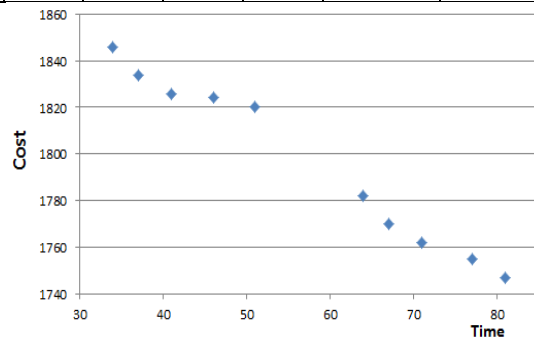


Figure 4.7 NSGA2 solutions

Furthermore, one can see the comparison between the best solutions achieved with iterative bidding process and its dominated solution obtained by NSGA2 in Table 4.7.

Table 4.7 Comparisons between best solutions obtained from two algorithms

NSGA2		Iterative bidding process	
Time	Cost	Time	Cost
67	1770	68	1781

Considering the results, it can be seen that iterative bidding process time–cost trade-off problems can be transferred to a multi-objective optimization problem by emphasizing one particular Pareto-optimal solution at a time. Using this approach, for finding multiple solutions, the algorithm has to be applied several times, finding a different solution at each simulation run. In our particular test case, the authors

ran the iterative bidding process 9 times and achieve 5 different solutions. This algorithm took approximately 17 minutes to run (on a Pentium 2.4 GHz PC, programmed in Java) Akanle & Zhang, (2008). As it is shown in Table A.2, after running the algorithm 9 times, it was able to find 5 different Pareto-front solutions. Therefore, the computational time for finding these solutions was approximately 85 minutes. However, implementing a spreadsheet model and using a DSS NSGA2 optimiser (Savić, Bicik, & Morley, 2011) (on an AMD Athlon 2.21 GHz PC with 1GB RAM) took only 10 seconds. The ten different nondominated solutions have been obtained. Solution No. 6 is better than the best solution found by iterative bidding process. Finally, as the best solution obtained from iterative bidding process (time=68, cost= 1781) is dominated by the best solution obtained by NSGA2 (time= 67, cost= 1770) it is eliminated from the best non-dominated (first rank) solutions. This solution, however, could still be found in the second rank of the solutions. Thus, this test case shows the ability of NSGA2 to find multiple Pareto-optimal solutions in one single simulation run. This confirms with what (Deb et al., 2002) claimed in his research paper.

Apart from this, since iterative bidding process was originally designed to optimise production planning in manufacturing systems, it therefore has mostly been tested on a simple component with a limited number of operations. Looking at the data collected in the case study in Chapter 5, the average number of the nodes in project networks is 28. Furthermore, the precedence relationship between activities is not simple sequenced. The above test case considers only the finish to start precedence relationship with zero time lags. Thus it seems that applying the iterative bidding process as an optimising tool may take too long and that the DSS that may be developed by this method would not be suitable for practitioners.

This argument is in conformity with Homberger (2007) when he claimed that project scheduling problems are involved with complex and large activity networks while manufacturing scheduling problems are based on simple and few precedence relations between the tasks. He therefore claimed that although many scholars proposed several methods for solving decentralised manufacturing scheduling problems using MAS, the majority of these methods are not suitable for solving multi-project scheduling problems.

According to the above analysis, the NSGA2 is adopted as a very good substitute for the optimisation engine of DIMS. It will be shown how it is utilised in the proposed framework in this research to find a Pareto front of solutions for each individual project in the field of multi-project construction management. This is similar to the DIMS concept where agents interact, coordinate and collaborate with each other to find the optimal solution for multi-project planning at the tactical and operational levels. In order to do this a project manager agent will be enhanced with NSGA2 as an external programme to deal with trade-off problems in the proposed multi agent system architecture. The details of the method will be illustrated in Chapter 6, Section 6.7.3.1.

In spite of the above mentioned pitfalls, the DIMS concept is suitable for hierarchical multi-project scheduling. In addition, it gives sufficient insight for developing a proper framework and model that could start from project scheduling and end up to the supply chain configuration. The agent based blackboard architecture and knowledge database that support coordination between different orders to come up a supply chain configuration, could be utilised in construction hierarchical multi-project planning. This will be also explained in detail in Chapter 6.

4.9 Summary of the adopted models in hierarchical planning

In the past three chapters, different models were reviewed in the three decision making levels of hierarchical multi-project planning. In this section, the selected models are summarised to provide the basis for the rest of the study. The adopted models are categorised based on the operational, tactical and strategic levels and tabulated in Table 4.8.

As Hans et al. (2007) discussed, there are many overlapping processes between operational, tactical and strategic decision levels in hierarchical multi project planning. These overlaps were identified and highlighted in the table, according to the literature review as well as the case studies (that will be discussed in the next chapter).

Table 4.8 Summary of the adopted models and the identified gaps that need to be addressed

Decision level	Decision making	Requirement	Adopted model	Notes
Operational	Single Project Scheduling	Generalised Discrete Time-Cost Trade-off Problem	(Chassiakos & Sakellariopoulos, 2005)	It is a single objective model. It needs to be changed to a multi objective one.
Operational	Reactive scheduling	Rescheduling and changing a subcontractor if required.	No existing model.	According to (Herroelen & Leus, 2004) a model need to be devised for each specific industry.
Operational and tactical	Subcontractor selection	Quantitative +Qualitative assessment	(Arslan et al., 2008)	It provides a qualitative assessment. Modification required: quantitative measures like cost and time need to be considered.
Tactical and strategic	Project selection	Qualitative assessment	(Han et al., 2008)	The outcome of this model can be used for bid pricing, negotiation, and resource conflict resolving
Tactical and operational	Dynamic multi project scheduling	Considering a dynamic interval of the GDTCTP	Multi Agent System and DIMS Concept (Zhang et al., 2007)	Modifications required: 1- In DIMS generalised precedence constraints were not considered. 2- It is not able to provide Pareto-front curve. 3- Solution algorithm should change to NSGA2 (Deb et al., 2002). 4- A mechanism for resolving the resource conflicts needs to be developed and added to DIMS.
Strategic and tactical	Key Performance Indicators	Benchmarking KPIs and devising rule models	KPI Engine & Zone (Centre for Construction Innovation, 2013)	The website can be utilised for benchmarking. Rule models need to be developed.
Strategic	Supply Chain Configuration	Subcontractors need to be clustered.	Akanle & Zhang (2008)	Probability clustering model needs to be modified for using in the construction industry.

Although all the researchers believe that the planning and scheduling of the project plays a critical role in all the processes of the project based organisations, they have ignored the integration of project planning with other decisions such as supply chain design and configuration, project selection, bid and no bid decisions and also system adaptation mechanisms with response to uncertainties. For the

construction industry, the hierarchical framework must also be able to provide a viable basis for negotiation with clients to increase the chance of getting a new project in a bidding process in very competitive market resulting in reducing the sleep time.

Thus the proposed framework in this study as will be illustrated in Chapter 6 was devised to address these requirements and provide a platform for improving the communication and negotiation between all parties involved and adapting the whole system in response to uncertainties in the construction industry.

4.10 Summary

In this chapter, the complexity of multi-project management was discussed. Dynamics and uncertainty are known as two main aspects that lead to complexity. Learning from uncertainty seems to be one of the important levers that can facilitate managing complexity. There is a lack of capturing and transferring the lessons learned from past projects to the whole of the organisation for planning and managing new projects in the portfolio. Therefore developing a framework and a system platform that enable the portfolio management to capture and transfer past experience to the whole of the portfolio could be vital to project portfolio management.

Moreover, DIMS technology that has been proposed for integrating several decision layers in manufacturing systems has been analysed. Although DIMS was identified as an alternative methodology for addressing the required integration between several decision making stages and overcoming the drawbacks of studies in multi-project planning, the gap analyses showed that to achieve this, it needs to be redeveloped and promoted. Finally in last section, all of the requirements of developing a system framework were recapped and summarised. This and the findings from case study that will be discussed in Chapter 5 are the bases of the designing of the proposed hierarchical multi project planning framework for the construction industry.

CHAPTER 5 CASE STUDIES IN THE CONSTRUCTION INDUSTRY

5.1 Introduction

So far existing theoretical models in hierarchical multi-project planning and its levels (i.e., strategic, tactical and operational) have been reviewed. As discussed in Chapter 2, Hans et al. (2007) argued that a model for hierarchical multi-project planning should accommodate the complexity and uncertainty of the enterprise environment targeted for the study and also should be practical and suitable for practitioners. Bearing these in mind, as this research aims to construct a hierarchical multi-project model for construction industry based on academic research methods, in the previous chapters the author reviewed various aspects and functional requirements in the literature in order to understand the dimensions of the complexity in the project portfolio management and supply chain operations with emphasis on the construction industry.

However, according to Meredith et al. (1989) “the most valid information is that obtained by direct involvement with the phenomenon”. Therefore, the next step, as defined in the research methodology was conducting a case study in order to understand the details of activities, processes, functions and system requirements that practitioners undertake in real world construction industry.

Conducting in-depth case studies in construction companies was designed in the research methodology as discussed in Section 1.6. Collecting information from projects was the best way to understand how practitioners negotiate with clients, and manage project portfolios and the associated supply chains. In addition, the author was able to understand how they identify, assess and mitigate risks. Dealing with the tendering process, project planning and control and risk assessment in a real construction case study was a great opportunity to understand how practitioners conduct these processes and to determine the gaps between theory and practice.

The data were collected gradually by being in the context for over 11 months and building up a close relationship with the practitioners from different layers of the project organisation. In addition, when the management team of the company was handing over the final phase of the project, a system prototype presentation was delivered to the director of the company and two of the project managers followed by a semi-structured interview in order to verify the system, which triggered the next step of the research methodology in system design. This raised the awareness of some other strategic issues particularly in tendering and project risk assessment that is currently used in the case study company. Therefore, in the revision of the proposed framework, the author emphasised different aspects of uncertainty within the project and entire enterprise supply chain. This resulted in the second version of the framework that was presented to the other case study construction companies including four other companies and interview with 11 practitioners. The valuable feedback gathered in order to validate the practicality and usefulness of the proposed integrated enterprise framework.

In this chapter, first the author introduces University Partnerships Programme (UPP) and describes the details of the findings from conducting observations and interviews from over 11 months direct observation and involvement with their business processes. Then other companies that have been investigated for the purpose of validation of the entire framework will be introduced.

5.2 UPP

UPP is the trading name of the UPP Group of companies – “the UK’s leading provider of managed on-campus university accommodation”. The Group specialises in establishing long-term partnerships with universities to fund, develop and operate student accommodation. UPP is a founding member of the Committee of Management of the ANUK Code of Standards, designed to improve student accommodation (UPP-ltd, 2013).

At the time of this research, UPP was managing the construction of student accommodation as University of Exeter’s partner. The portfolio included construction of 2000 student accommodation room totalling nearly 50000 square

metres within three years. The appointed general contractor for this project was Cowlin Construction (a part of Balfour Beatty). Since the volume of the project was high and also because it was geographically close to me, I chose this as case study company based on advice in the literature for selecting the case study company (Stuart et al., 2002).

The purposes of the case study were to understand the real word problems and compare the theory with the current practice in decisions making process in different hierarchical levels as well as validating with practitioners the initial proposed model (which will be explained in Chapter 6). The in-depth case study was conducted for four reasons,

- i) to understand how practitioners, including clients, portfolio managers, project managers, site managers, subcontractors interact and coordinate with each other to achieve each project's objectives;
- ii) to collect detailed information including contract and project specifications, current plans and schedules, monthly progress reports, specifications for subcontractors and their bid information along with their capacities and capabilities and the ways of evaluating them;
- iii) to understand the procedures of risk management in the case study company and to compare them with the literature in construction industry;
- iv) to find out how the available theoretical methods could be utilised practically in the construction industry.

In the following subsections details of the case study process will be explained.

5.2.1 Data collection

As mentioned, in this case study several methods for data collection have been adopted as follows.

5.2.1.1 Direct observation

For collecting data, direct observations and site visits along with formal and informal communications were carried out while photos and videos from progress of the project were taken. Apart from monthly site visits, more visits were held on

several special occasions such as delivering products, starting/finishing the job of a particular subcontractor as well as observing the handover process.

The duration of each site visit and the informal interviews varied between one to three hours. The interviews were focused around the theme of how the company deals with a call for bid from clients, how they select subcontractors, how they establish their master plans and update their progress, how they coordinate with subcontractors in order to control the project based on the master plan, how they reschedule the master plan and how they assess risk and uncertainty.

5.2.1.2 Documents

Documents such as original contracts and the prices, collected bids from subcontractors for each particular work package, master project plan, monthly progress reports and updated schedules, along with several related items were collected.

Moreover, the details of contracts between UPP and University of Exeter and also UPP and University of Reading were provided to the author for gaining a better understanding of the business and tendering processes. Due to confidentiality in the competitive market, the author was not allowed to publish sensitive information.

5.2.1.3 Interviews

While site visiting and through thorough discussions and informal interviews with UPP's project manager, and also Balfour Beatty team such as site managers, project engineers and quantity surveyors as well as observations from projects, the data were gradually collected during nearly one year's close relationship with the project organisation.

Finally, in September 2012, when the construction project was handed over to the client, a formal presentation meeting was held with four practitioners including the contract manager of the University of Exeter, the Group Construction Director and two project managers from UPP. A prototype MAS-DSS was presented and the evaluation was carried out by the practitioners in order to validate the plausibility and usefulness of the proposed method. The meeting was recorded, transcribed and analysed in order to validate the system and revise the framework if required.

The practitioners provided insightful comments for tuning the proposed approach particularly for the automated bidding process, subcontract selection and bid preparation processes. In addition, there was a discussion regarding risk management practices in the company which supports Atkinson et al.'s (2006), Wood & Ellis's (2003) and Laryea & Hughes's (2008) findings. The practitioners strongly accepted the proposed system as a holistic method for managing the tender process and project planning in construction industry. This will be discussed in Chapter 7.

5.2.2 Collected data

In this case study, I focused on the construction of three student accommodation buildings as my pilot study. These constituted 440 students rooms out of 2000 rooms as a part of a huge investment based on strategic development plans at University of Exeter. The total amount of investment was over £77m and took nearly three years. The construction of these three buildings started on October 2011 and was finished on time as the third and last phase of the contract. UPP was in partnership with the University, and jointly managed and controlled the performance of the General Contractor and its subcontractors. Cowlin, a part of Balfour Beatty, was the general construction contractor. The reason UPP was selected by the University as its partner was that it had the relevant experience and skills from undertaking several similar projects across the UK. They have developed specialist skills and are reputable as they have a management team who can coordinate appropriately between different parties across the whole of the supply chain. The specification of these three buildings is shown in Table 5.1.

Table 5.1 Accommodation blocks ongoing projects at the University of Exeter “pilot study”

Block No.	Number of storeys	Specification	Floor Area m ²	Total GIFA*	Start date	Promised date
2	6	190 en-suite bedrooms	750	4500	12/12/11	03/09/12
3	6	190 en-suite bedrooms	750	4500	14/11/11	22/08/12
4	4	60 en-suite bedrooms	356	1424	17/01/12	24/04/12
*GIFA: gross internal floor area						

The nature of the construction of these three buildings and the activities and the work breakdown of them was generally the same. In fact, UPP, based on its previous experiences, has prepared a “bible” for its own projects and customized their maps and plans for all accommodations that they build. By doing this, they reduced the designing cost. Moreover, any changes based on customer’s request can be accommodated very simply and quickly.

The first level of work breakdown (WBS) of the construction of an accommodation block that is classified based on their approved suppliers/subcontractors is listed in Table 5.2. It should be noted that, for the sake of confidentiality I was not allowed to provide any more detailed data. However, it should be noted that, for each line of the WBS there were a number of certified subcontractors along with their corresponding cost and time.

According to the UPP procedures, apart from the general contractor, all of the subcontractors should be assessed by the management team. Therefore, they have established a supply chain that is categorized based on their capabilities and expertise. So, UPP has a number of certified suppliers/ subcontractors for undertaking each part of the work breakdown of a building. At the beginning of each project, the project manager takes part in several meetings along with the appointed general contractor and negotiates with several subcontractors to investigate which ones are interested to put forward bids for a particular section of the work breakdown. In fact, the eligible subcontractors should compete with each other for undertaking one part of the project’s work breakdown. In doing so, they calculate the volume of the proposed work and estimate the time and cost of the job. Finally, they put forward their bids. Therefore, the time and cost of each part of the work breakdown could vary depending on the subcontractor’s evaluations and their competitors. Then the project manager aggregates the best bids to find what is the minimum price and time for construction of any single project. Of course, he/she selects the best collections which satisfy the constraint of completing on time.

According to the monthly reports of UPP at the end of October 2011, more than 1100 individuals across the approved subcontractors and supply chain were working for University of Exeter as portfolio resources.

Table 5.2 Top-level WBS of a student accommodation block.

WBS ID	Work Breakdown Description	WBS ID	Work Breakdown Description
1	Ground works	15	Cladding
2	Scaffold	16	Cladding Rain Screen
3	Timber Frame	17	Mastic
4	Pods	18	M&E etc
5	Door/frame etc	19	Ventilation extract
6	Stairs	20	Fire stopping
7	Roof finishes	21	Carpentering work
8	RWP's	22	Decoration (Mist, Ceilings, Coats)
9	Dry Lining/Plastering	23	Carpet (rooms/ communal)
10	Acoustic floor	24	Furniture/Kitchens
11	Windows (uPVC)	25	Mattress & Workstation/ chairs
12	Windows (composite)	26	Curtains
13	Lightning Protection	27	Suspended Ceilings Grids / Tiles
14	Brise Soleil	28	Cleaning

5.2.3 Findings from UPP

The collected data from documents, informal and formal interviews, and direct observation, gave insightful vision to the hierarchical multi-project planning in construction industry where subcontractors play the critical role in businesses success. Some of the facts and findings elicited from direct observations and informal interviews are as follows:

- 1- When selecting subcontractors, project managers visit subcontractors' sites and suppliers' factories in order to evaluate their capabilities and capacities. Although project managers provided their evaluations for each subcontractor, there was not a unique format, method and subsystem for

this purpose. Therefore each individual project manager provided its report to the company (Group Construction Director) based on its own format.

- 2- The portfolio manager, Group Construction Director, who is responsible for negotiating with the clients chooses the projects to add to the portfolio and works closely with the project managers for bid preparation purposes.
- 3- The project is broken down into work packages. Then, for each work package at least three bids are collected from subcontractors by project managers.
- 4- Their current attitude is choosing the subcontractor with minimum bid price however they also compare the quality of the proposals as well.
- 5- The negotiation and contracting is a demanding process that company is involved with for each particular client. This process sometimes takes several days with high qualified and knowledgeable clients (universities).
- 6- Project managers are responsible for controlling the on-going project by leading the steering committee.
- 7- Starting and particularly terminating each project causes huge disturbances across the project organisations. For instance many experienced personnel were leaving the company, in anticipation of the end of their project. There are two examples here:
 - a. The site manager of block 3 left the company just 3 months before finishing the project.
 - b. The site engineer, who had joined the project at the early stage of the project life cycle, left the job and went to Bristol to work in another project four months before the end of Exeter's project.

When I asked them the reason why they decided to leave the company before finishing the project, they both said "because we need a job. We are not sure after this job we would be able to find a good job in the right time with Cowlin". They both were cautious about "sleep period", based on their previous experiences.

- 8- The company replaced each of them with very young and inexperienced staff in a very critical period of the project life cycle. So it caused some difficulties for the Project Director of Cowlin.

- 9- The “Sleep Period” for the Cowlin team took more than 8 months where the Project Director and a few young engineers were looking forward to the start of a new project which was under negotiation with new clients.
- 10-Despite these problems the project was handed over on time to the ultimate client i.e. University of Exeter. This increased the reputation of UPP and raised their chance to be winner in further projects.
- 11-Although UPP’s success was because of their close work with Cowlin, in the next project they did not continue working with the same company. This shows to the weakness of the supply chain links in construction industry in the UK.
- 12-The project manager of UPP was appointed to another project at University of Reading. He was trying hard to find the same team members to work with him on his next project. However, despite his endeavour to recruit the staff in the next project, he failed to convince them as they had found better jobs before finishing the Exeter’s project.
- 13-Although Group Construction Director tried to support the team working between his project managers (in this case, the project managers of Nottingham and of Exeter), there was no systematic approach for sharing their knowledge and experience). Therefore a mistake that happens in a site might happen in another site.
- 14-Each individual project manager set up his own supply chain and minimum information sharing was available for other project managers with regards to experiences of using a particular subcontractor in a distributed portfolio organisation.

The data and particularly the main issues that were raised in the last interview shed light on ways of revising the initial framework to resolve and accommodate the main barriers to the management of the complex construction project. It was understood that sleep time in construction industry causes serious problems for the supply chain configuration. Therefore, the proposed framework was improved to reduce the sleep time as much as possible by facilitating the bid preparation and negotiations between a general construction company and its clients. The final version of the proposed model will be explained in Chapter 6 and the formal

feedback that was received from the management team of UPP will be explained in Chapter 7.

5.3 Other case study companies

Based on the findings from the first case study company, UPP, the author designed an integrated decision making system framework. This framework encompasses the requirements of process integration in construction industry. This integration is based on a wide range of business processes from operational and tactical tender and client negotiation processes, to strategic supply chain configuration. Although the proposed system was presented to the practitioners in UPP and their feedback was collected as a validation exercise, a series of presentations and semi-structured interviews were conducted in some other companies in order to evaluate whether the proposed system was suitable for other general contractor companies. This can be referred to as “external validity” (Voss et al., 2002) in the current study.

As Barratt et al. (2011) suggests, the rigour of research can be assured through conducting four or five case studies. Therefore, in this research apart from UPP, three other construction companies were selected to investigate how the framework can fit with their requirements and how it can bridge the existing gap between different processes across the business. The construction companies are listed in Table 5.3.

Table 5.3 Case study companies for external validation

Company	Location	Department	No. of Meetings	No. of practitioners
Kayson Inc.	Iran	1. Business Development and Pre-Qualification Department 2. Contracts and Tenders Department	2	4
Interserve Plc.	UK	1. Exeter Regional Office	1	3
Fanavaran Co.	Iran	Director, Finance, Construction	5	3

The selected companies were national and international, from different sizes and different types of organisational structure. For each company a single presentation meeting was planned. However, their interest to explore more of the proposed framework led to planning more meetings. In the large scale organisation (i.e. Kayson), this led to deeper evaluation conducted with different expertise from

different divisions of the company as the integration of the framework and processes were required to be evaluated by process owners. When the size of the company was relatively small (i.e. Fanavaran) the CEO directly participated in the meetings and his evaluation was investigated as he was able to evaluate the entire framework.

In each presentation and interview, feedback was collected and analysed based on a validation sheet that had been designed for this purpose. In Chapter 7 the feedback of the management team of each company in relation to the proposed model in this study will be explained. In the following subsections a brief introduction of each case study is provided.

5.3.1 Kayson Inc.

Among the selected companies, the largest one is Kayson Inc. which is ranked as 139th largest construction company across the globe (Engineering News Records (ENR), 2013). Kayson is a privately owned engineering and construction company providing world-class design, management, procurement and construction services to develop, engineer and build projects for customers both in Iran and overseas. It has devoted a sizeable portion of its resources to strategically penetrate attractive markets around the globe: Equatorial Guinea, Algeria and Sudan in Africa; Kyrgyzstan, Kazakhstan and Belarus in the ex-Soviet bloc and Venezuela in South America.

The chief operating officer who is also member of the executive board is responsible for five construction divisions including, oil, gas and industrial division, housing division, civil and building division, railway transportation division and water & waste water division where an advisory team and a technical committee provide the required service to him. The tenders and contracts manager works under the supervision of the chief operating officer and provides services to all of these divisions (Kayson, 2013).

Business Development department and also Planning & Business Excellence department were two other organisational sections that were involved with the case study. These departments are working under the responsibility of two other chief officers namely Chief Coordinating Officer and Chief Resource Officer. The first

interview was conducted with these departments and their interest led to the holding another meeting with Tendering and contracts department. In total, approximately 12 man-hours were spent on presentations, evaluations and further feedback. The outcomes of the interviews will be explained in Chapter 7.

5.3.2 Interserve Plc

Interserve is also one of the internationally recognised support services and construction companies, operating in the public and private sectors in the UK, Europe, Middle East and East Asia. It offers advice, design, construction, equipment and facilities management services for society's infrastructure. It has several active sites and offices across the globe such as Ireland, Portugal, Spain, Germany, Qatar, Bahrain, UAE, and also Australia, South Korea and Hong Kong. The Managing director of Interserve Development is responsible for infrastructure and private finance initiative (PFI) projects in the construction division. Interserve provides a range of capabilities including Building, Civil Engineering, Water treatment and Waste, via relevant subdivisions.

Nationally, Interserve operates a network of regional offices in key locations, delivering projects across the UK. Each office has the flexibility and expertise to offer a comprehensive range of building and refurbishment services. In the south west it has three Regional Offices (Interserve, 2013).

In this case study a presentation meeting and interview with the management team in Exeter regional office based on a refurbishment project of the University of Exeter has been conducted. The outcomes of this case and interview will be analysed in Chapter 7.

5.3.3 Fanavaran Co.

Fanavaran is an Architectural and Urban Development specialist company. It also offers Engineering, Procurement and Construction (E.P.C) projects. It is classified as a small to medium sized (SMEs) national construction company. Its focus is on constructing bespoke residential and commercial buildings across Iran (CECTD, 2013). One of its major clients is Pasargad Bank. It is a relatively new private bank in Iran which was established in 2005 based on the government policy of privatization of the banking system. The Banker Magazine has ranked the Bank

as the 266th bank amongst the world's 1000 top banks, while being one of the 10 highest movers of the globe and the highest mover of the Middle East (Bankpasargad, 2013). From the beginning of the establishment of this bank, Fanavaran has designed and constructed a number of commercial buildings (over 48000 m² in four major cities) and has also built or refurbished over 100 branches of this bank, i.e. one third of its total branches across Iran (in total over 32000 m² in 26 provinces) which turned Fanavaran into the a permanent collaborator of the bank in construction activities. Apart from other private clients who are looking for special and bespoke architecture and top quality construction buildings, the strong track record of the company helps expand the market with other Private Banks in Iran such as Eghtesad-e-Novin Bank, Bank-e-Sina and Tose'e Ta'avon Bank. So, the demand of design and refurbishment projects is increasing for new established private banks and there is a potential market for conducting this kind of projects for old state banks as well. Apart from the information collected through interviews, documents and archival data regarding the bank branch refurbishment project database was also given to me in order to understand the supply chain dimensions and the distribution of the projects across the country. On average, this kind of project took approximately 50 working days from architectural design to handing over to the Bank. In this market, Fanavaran uses some specialist subcontractors in security systems and electronic and networking systems that are based in Tehran. This company has also configured a network of local subcontractors in major cities in a number of provinces which could take the advantage of utilising local builders, carpenters, etc.

The initial aim of approaching this company was to present the proposed model and to obtain their feedback as an external validation, but the CEO became effectively engaged in the evaluation process. He enthusiastically shared his experiences through open-ended formal and informal interviews and offered data related to their current construction project. This process led to providing more detailed information about other projects as well, particularly the Khatam University project. It was introduced to me as an ongoing project and site visits and direct observations were conducted. The theme of the meetings was around the issues that arose during this project with Pasargad Bank and how the proposed

framework could resolve the pitfalls and existing conflicts between company and its strategic client.

5.3.3.1 Khatam University

Khatam University is the main educational division of Pasargad Bank. The University has recently become a part of the Bank for training purposes in higher education. The main building of the University is an eight storey building of over 13000 gross internal floor areas (GIFA) located in North Tehran. The building was bought by the Bank in March 2013 when its framework had been finished. The Bank asked Fanavaran to design and to carry out the finishing phases.

The target was very tight. The project was given to Fanavaran in the last week of April 2013 and was to be finished for the next academic year i.e. the last week of September 2013. Since Fanavaran had established a good reputation for on time and fast delivery projects, the Bank chose it in order to achieve this tight goal. The time limitations forced both clients and contractors to close their eyes to time-consuming contracting processes. So Fanavaran started the project and put this job in its portfolio with the highest priority in hope of increasing its reputation and also profitability. The project was started based on a cost-plus approach with monthly claims. The architectural design was started very quickly and led to high level of work for the architecture team. They worked in three continuous shifts for over 5 months parallel with the builder's supervisory group. The designs and plans were being done on a daily basis; the work schedule was planned upon receiving the drawing and builders were acting fast and working in two long shifts. This might be a good example of "Agile Construction" as discussed by Ribeiro & Fernandes (2010). In addition, as the contract was cost-plus and also because the location was in Tehran, the Bank opened a supervisory team office in the project in order to control the project progress. They were controlling the project's progress and pushing the contractor to minimise the expenditures. Therefore, this might be also a good example of "Agilean Construction" as discussed in (Demir et al.,2012). At the time of conducting this case study between mid-August and mid-September 2013, the building was nearly ready for operation. Apart from supervision by the Pasargad Bank, final approval for this building from the Ministry of Science, Research & Technology (MSRT) was required as the building was to be used by a

University, another challenge in design and executing the project. The author had the chance to conduct direct observation of the ongoing project. Several informal and formal interviews were carried out with the Engineering and Finance managers and particularly the CEO of the company. There was also a meeting with the client's representative that took place by arrangement of Fanavaran's CEO. Although by spending lots of effort and working 24/7 the project was finished on time and the University was able to start its programme at the beginning of the academic year 2013-14, the work pressure and stressful condition of the project raised some conflicts between the company and its strategic client (Pasargad Bank). The lack of an adequate relationship between the company and the client's representative, who was appointed to work fulltime for supervisory purposes, created several conflicts and made the project's progress stressful for the company. Since the contract was cost-plus and the contract terms were not written well, this also caused several misunderstandings between the client and contractor. In addition, the client representative was interfering in details of the contractor activities and was trying to make direct orders to the trades and subcontractors. In some cases even the client's representative appointed its own subcontractors and disturbed the role of contractor management team in relation on their duties. Since the payments should be approved by the client's representative, some of the subcontractors were also confused about to whom they should listen. Despite these hard circumstances, Fanavaran managed to deliver the project on time. However, they became more aware of the importance of contract negotiation before starting projects. Moreover, one of the lessons that they learned and shared with me was to emphasise utilising their prequalified subcontractors in any conditions. The subcontractors should be set and fixed at the beginning of the project and the list of them should be approved by both contractor and clients. This case shows that despite a long-term partnership agreement between the Bank and Fanavaran, how the project management relationship can be affected by the behaviour of the client's representative in this project. These conditions were the main reason why the Fanavaran's management team became interested in utilising my proposed system in their company. The feedback from in-depth analyses of the details of proposed processes through a kind of action

research provided strong confidence of using the proposed method at the company. Some more meetings were held in order to train the staff with some details of the proposed framework particularly time-cost trade off preparation, subcontract selection and negotiation procedures. The details of the evaluation process that was carried out by the company's top management team will be discussed in Chapter 7.

5.4 Summary

It is known that in most countries the construction industry is extremely fragmented. The main reasons are poor communication and the lack of coordination between different actors and the lack of integration between different functional disciplines across the project supply chain and enterprise supply chain (Albaloushi & Skitmore, 2008).

Conducting the case study within several construction companies revealed that developing an integrated decision making enterprise system framework for hierarchical distributed multi-project planning that could support knowledge management and organisational learning is a crucial need for success of the companies.

Therefore, while data collection and observation of the project has been undertaken from a market leader company, the system requirements were investigated in order to identify the required methods for establishing this integration. These led to designing and testing a holistic framework that integrates several required functional processes in the construction industry in a dynamic manner. In the designed framework, operational, tactical and strategic decision making processes are integrated in a MAS-DSS prototype solution that will be explained in the next chapter.

CHAPTER 6 THE NEW SOLUTION FOR MULTI - PROJECT PLANNING AND SCM

6.1 Introduction

In the previous chapters, the author investigated different interdependent decision making requirements in complex project portfolio management and supply chain operations. The literature review included project selection, subcontractor selection, bid and tendering processes, project planning and scheduling with emphasis being laid on construction industry. Particularly, uncertainty and risk management in the construction industry were reviewed. Having extensive communication with practitioners and observation from the real construction project helped to find the gaps between theory and practice and also to identify the ways to improve the business process based on academic methods. The author understood that integration of these processes could help to improve the business processes in project portfolio management and supply chain operations. In line with the arguments of Winter et al. (2006) that identified the future research directions in project management, the author sought to design an integrated framework and its associated rules, based on academic research so that it would suit practitioners who work in general contractor enterprises. For doing so, the framework has been designed and validated in two sequential stages with a number of practitioners in market leader construction enterprises.

In this chapter, the proposed framework will be discussed. Since project portfolios are distributed geographically, the framework utilised a distributed architecture so that the autonomous decision makers i.e. project managers are able to make operational and tactical decisions while the portfolio manager controls the overall performance of the enterprise. Several mathematical methods have been adapted to make this integration possible across the three decision making levels including operational, tactical, and strategic decisions. This integration helps to cope with the complexity of the system environment. In addition, the multi agent decision support system performs as an adaptive system to identify the strengths and weaknesses

of the system when the market changes. Therefore it can be achieved by the implementation of the framework across the different divisions of the enterprise.

Since this framework includes several independent decision makers, it is able to integrate the strategic decisions of supply chain design with the tactical decisions of project selection and finally the operational decisions of project scheduling in a dynamic uncertain construction environment.

In this chapter, first the hierarchical framework will be introduced. Then the MAS-DSS architecture will be presented. The role models and interactions between actors will be described. Since each role should be undertaken based on one or more rules, later, the rule models will be presented. Different rules have been adopted and some adaptations have been applied in order to facilitate the integration across the entire framework as it is operated by several autonomous agents such as project managers, the portfolio manager, clients and subcontractors. Finally a summary of the chapter will be provided in the last section.

6.2 Hierarchical integrated multi-project management framework

As discussed in Chapter 2, there are a few hierarchical frameworks (Neumann et al., 2003), (Hans et al., 2007) and (Aritua et al., 2009) that propose how enterprises should deal with strategic, tactical and operational decisions in multi-project planning. However, these frameworks do not propose a specific methodology that enables the business to integrate these levels dynamically based on an adaptive and learning mechanism.

In this research work, the author proposes a hierarchical dynamic integrated framework that enables enterprises to make different interrelated decisions including supply chain configuration and coordination, project selection, subcontractor selection and project scheduling in a dynamic and interconnected manner in uncertain and complex project portfolio enterprises. The proposed framework is shown in Figure 6.1 and the implemented features of the framework in this study are highlighted by the dashed area.

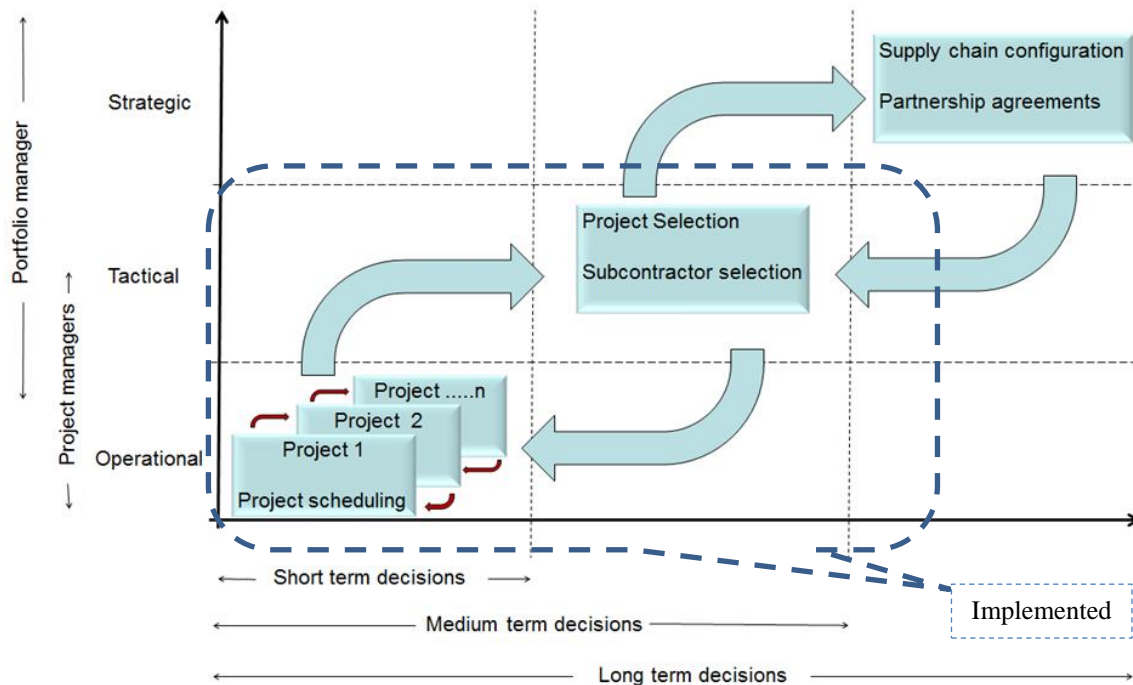


Figure 6.1 Hierarchical integrated multi-project planning framework

This framework can facilitate decision making processes by providing the appropriate mechanism at each level. At the operational level, where distributed projects need to be scheduled, it helps autonomous project managers to establish the master project schedule for each individual project associated with a particular client. However, a conflict might arise between different project managers when they want to use a specific resource (subcontractor) in a specific time window simultaneously. This conflict can be managed by utilising a tactical decision made by portfolio manager when different projects are assessed, ranked and selected in order to satisfy the enterprise profitability and reduce the risks. This decision will be made by the expert or practitioner in the real word environment based on a subjective risk analysis. These two levels of decisions, i.e. tactical and operational, are dynamically interrelated to each other and support with a negotiation mechanism that seek to increase the chance of winning the tendering process in construction industry. More specifically, each project manager who is responsible for preparing the tender document will utilise a multi objective optimisation genetic algorithm (NSGA2) as explained in Section 4.8, to propose a range of non-dominated solutions to the portfolio manager. This set of solutions will be negotiated with the client by portfolio managers in order to increase the chance of

being a winner in the tendering process with other competitors. These decisions that should be made in an uncertain business environment effects project supply chain configuration or subcontractor selection decisions. Therefore, shorter term decisions related to project planning are entirely dependent on longer term decisions for project selection and subcontractor selection.

While the portfolio manager tries to increase the chance of winning more projects in the tendering processes, the sleep time of the enterprise supply chain will be reduced and subcontractors with higher capabilities tend to be selected more frequently by project managers for the future projects. At the operational level, after finishing each project an evaluation subsystem will be utilised by project managers in order to update the rating of the subcontractors. In addition, a feedback subsystem tracks the market environment by benchmarking the enterprise key performance indicators (KPI). It means that the KPI will be calculated and compared with competitors in the market. Therefore, the negotiation model that is utilised by the portfolio managers in connection with clients can be adapted to increase the chance of winning a potential contract that in turn results in sleep time reduction for the enterprise supply chain. The framework seeks to minimise the sleep time so that the subcontractors will be encouraged to work more competitively with the company with a lower profit margin because the continuity of work provides them more confidence for their future planning. This should help to establish a sustainable and resilient supply chain. It leads to enterprise supply chain configuration and partnership agreements in longer term decision making in strategic level. The feedback sub-system helps the framework to continuously track the reliability and capability of the subcontractors so that after running the model for a specific number of the projects or a specific time window, more frequently used subcontractors can be clustered and supply chain reconfiguration will be conducted eventually. Hence, this framework works based on the feedback loops that dynamically link different decision making levels including operational, tactical and strategic decisions.

For implementing this framework a multi-agent decision support system architecture is proposed and the role of each individual autonomous agent is illustrated in the next section.

6.3 Architecture of the proposed model

A Multi Agent System, Decision Support System (MAS-DSS) is designed to facilitate the coordination and cooperation between several autonomous involved parties who are scattered in different locations and responsible for one or more decisions collaboratively.

In this research the MAS-DSS is designed based on a hybrid architecture including both reactive and deliberative agents (Wooldridge & Jennings, 1995). The reactive part is responsible for collecting data and interacts with environment that it recognises as different actors including clients, portfolio manager, project managers and subcontractors. The deliberative part includes several reasoning models that facilitate the process of decision making in different levels of the hierarchical framework illustrated in the previous section. Therefore, the proposed hybrid system was designed based on both reactive agents (in order to acquire information via communication by different actors who acts independently) and also deliberative agents (that enable system to facilitate planning and optimising decisions across the complex project portfolio and its counterpart supply chain). Figure 6.2 represents the architecture of the proposed MAS-DSS.

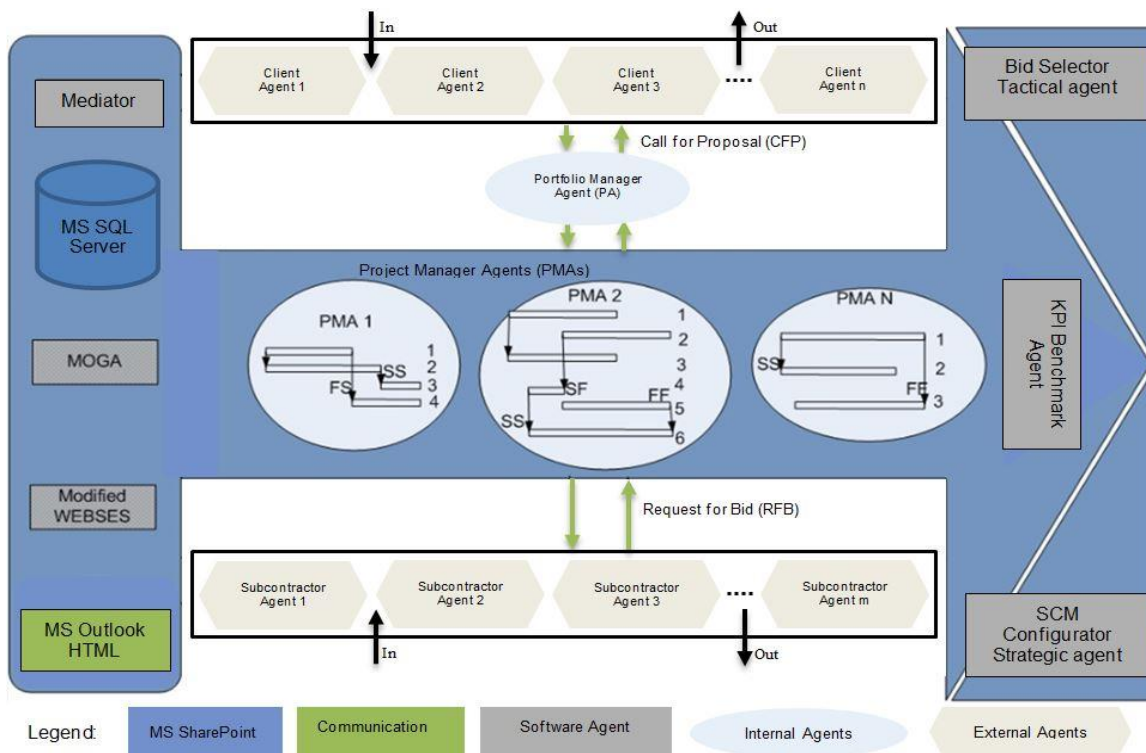


Figure 6.2 Multi-Agent architecture of the multi-project planning and supply chain management

First, the human agents and their responsibilities are defined.

Client agents (CA): are the owners of projects. It is an external actor that communicates with the enterprise in the tendering process as well as evaluating the quality of the finished project. Each project is associated with a client. Clients negotiate with the project portfolio manager, to make the contract decisions.

Portfolio manager Agent (PA): represents the company's project portfolio manager who globally manages the portfolio. His responsibilities are receiving the "Call for Proposal" (CFP) from CAs, selecting the project (bid/no bid decision), assigning weight or value to the potential projects, coordinating with project manager agents to prepare a bid for each CA, negotiating with CAs. He is also responsible for evaluating and calculating key performance indicators and benchmarking. The supply chain configuration and partnership agreements decisions are made by the PA with the help of other software agents that will be illustrated later.

Project Manager Agents (PMAs): represent the company's project managers. Since projects are geographically distributed PMAs are autonomous decision makers with a number of responsibilities. When a project is allocated to a PMA by PA, the PMA is responsible for breaking down the project to several work packages and defining the precedence relationship between each work packages. Then the PMA negotiates with subcontractors in order to collect several bids for each work package. He is responsible for sending requests for bid (RFB) to subcontractors and receiving their responses, planning and scheduling the projects by using a combinatorial optimization technique in order to obtain time-cost trade-off schedules, collaborating with PA to finalise the proposal for the clients, and selecting the appropriate subcontractors. He is also responsible for controlling the project in real time actions and rescheduling the projects when it is required. Subcontractor evaluation is also his responsibility. The status of a project could be identified as no-bid (refers to project/bid selection phase as will be explained later), under negotiation, proposal submitted, rejected by the client, active or finished project.

Subcontractor Agents (SCAs): are associated with autonomous and self-interested enterprises. Their responsibilities are receiving RFBs, ignoring the RFB or sending a bid (estimation of time and cost of undertaking a specific work package of a project), and conducting the agreed work package. SCA status could be active or inactive. Their capacity and capabilities are altering over time. This information will be evaluated by the PMAs periodically.

In this architecture there are also several software agents as follows:

Moderator Agent (MA): represents a multi-agent blackboard and deals with registering each agent and updating their status. All the transactions and interaction are handled and controlled by MA in order to resolve conflicts and update the system database.

Bid Selector Agent: is a software agent that provides appropriate procedure and user interface to facilitate project selection mechanism. The portfolio manager along with Project Manager Agents can subjectively assess the received call for proposals (CFP). After collecting data, the agent invokes a particular procedure to facilitate bid or no-bid decision when the calculated score is compared with a minimum acceptance level. The acceptance level is controllable by the feedback system.

MOGA Agent: is a multi-objective GA procedure that will be invoked whenever a PMA has to deal with a time-cost trade-off problem.

Modified WEBSSES Agent: is utilised for evaluating and scoring SCAs. It is a modified version of Arslan et al's model as mentioned in the literature review. The full description of this procedure will be provided later (see section 6.7.2). This procedure will be invoked by the PMA whenever he/she needs to assess a subcontractor.

KPI Benchmark Agent: is a procedure that provides appropriate feedback from the performance of the system. This agent facilitates communication between Client Agents, Portfolio Agent and Project Manager Agents. The appropriate questionnaires are sent to and received from those agents. After collecting the required data, this agent is able to calculate the KPI of the projects and enterprise. In addition, this agent compares the enterprise KPI with the available norm existing

in the construction industry by accessing an external database to provide feedback to the system from its performance. This feedback leads the enterprise to further adaptations in connection with supply chain configuration and also bid/no-bid decisions.

SCM Configurator Agent: is also a software agent that determines the supply chain configuration for partnership agreements based on probability clustering approach for detecting the most frequently used suppliers/ subcontractors.

6.4 The Platform and Blackboard system

The system performs decentralised project portfolio planning. Microsoft Server and MS SharePoint provide a suitable platform to support integration and data handling between several project sites (project managers) as well as head office (portfolio manager). This platform facilitates collaborative work between internal actors, the project portfolio agent and project manager agents. It is worth noting that decision making process will be made by PMAs however the overall control of the number of active projects across the enterprise, allocating jobs to the SCAs and also measuring KPIs are integrated. A central blackboard database (SQL Server) is utilised in which the global system time, projects' status, PMAs's loads and competences, and also subcontractors' attributes (score, load and capacity) are kept and updated every time a new situation needs to be considered.

6.5 Communication protocol

Communication is a vital part of any multi-agent system. The author used MS Outlook protocol (Microsoft, 2013) to facilitate communication between client agents and portfolio agent and also communication between subcontractors with project managers agents. The reason for selecting this protocol was that it is used to transfer data across the globe. This provides a most widely used application for daily base email and message handling. In addition, most of the construction companies also use the same protocol for all of their correspondence. Therefore using this protocol raised the practicality and chance of being accepted by practitioners. In addition, it facilitates the integration with other commonly used software applications such as Excel and MS Project. Thus the proposed MAS-DSS

can be easily integrated with other business applications for further potential research studies.

6.6 Relationships and interactions of Agents

Since multi-project enterprises work in a complex environment including several independent and self-interested actors, the interaction between these actors should be investigated, identified, optimised and facilitated so that information can pass through across the system and help decision making in a proper time with minimum error. The interactions and relationships between agents are shown in Figure 6.3.

In real world market, clients announce call for proposal (CFP) randomly. Although these CFPs shape the market demand, the performance of the enterprise could increase or decrease the number of future income projects. This means that if the enterprise performs well, its reputation will be increased which result in more clients and more contracts. On the contrary, if the performance is not good, the reputation of the company will deteriorate and it may lose its market to its competitors. Therefore, in this research the author tried to capture this phenomenon.

In the architecture, while the MA controls the entire distributed system and updates the blackboard, the PA manages the tactical and strategic decisions. He makes decisions with regards to bid or no bid (refers to bid selection) as well as supply chain configuration and partnership agreement with key SCAs. In the construction industry these decisions are vital and affect the key performance indicators of the enterprise. KPIs will be evaluated and benchmarked with the construction performance database available on the web (see Section 6.7.6). He utilised the key performance indicators in order to accommodate the feedback and promote system adaptation.

These decisions are closely related to the decisions that are made by autonomous project manager agents. While they prepare the bid price they should carefully select the best subcontractors who are reliable and are able to provide sustainable services to the enterprise. In addition, project managers coordinate subcontractors

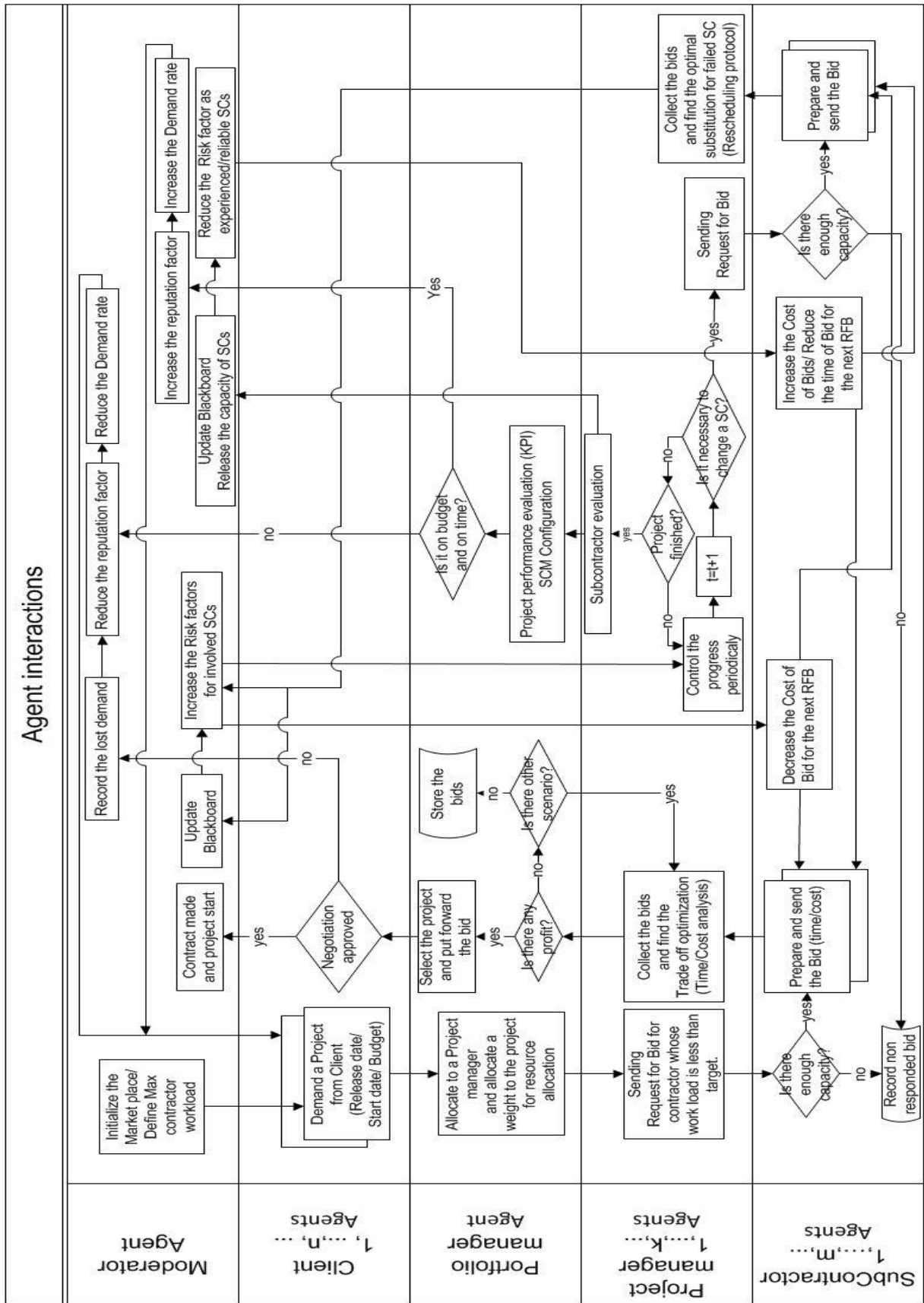


Figure 6.3 Complex dynamic construction multi-project system

to achieve the project goals in terms of time, cost and quality. The proposed model in Figure 6.3 focuses on these aspects of decision making and tries to integrate them in a multi-agent system platform.

It is worth noting that the final decision about agreeing the contract is made by the client agent and it is out of control of the enterprise. However, a general contractor tries to increase the chance of winning the tender by better coordination with its entire supply chain. Better negotiation with the client should be provided by the proposed interactions in this research work.

6.6.1 Description of the Roles

The MA initialises the environment and updates the blackboard. It initialises the other agents, and updates the capacity of the subcontractors; the capacity of the company for accepting the projects and the SCA's risk factors (evaluated scores). The workloads of the subcontractors and the company are also updated.

The process starts when a CA proposes a CFP defining the specification of a project to the PA. The CFP will usually specify the start date and project deadline. In contrast with other research work in the literature, there are no limitations considering the number of projects that could be entered into the system or their time intervals. Furthermore, the decision for replying to the CAs or not is made by PA. This refers to bid selection decision in construction industry. The details of the decision making rule in bid/project selection and bid preparation which are at tactical level of hierarchical framework will be explained in Sections 6.7.1 and 6.7.4 respectively.

It should be noted that the time intervals of the clients/projects are a function of the overall system performance according the KPI calculated in the previous period of time. In other words, if the key performance indicators (KPIs) of the enterprise increase, it will then reflect on the company's reputation. This would encourage the CAs to send their CFP to the enterprise. However, if the KPI become lower, it would bring a bad reputation (higher risk) which will result in less clients and longer time intervals between each CFP. This refers to the feedback and closed loop system where feedback could have both positive and negative impacts. Moreover, this rule plays the main role in the bid selection decision. The PA with higher

reputation is able to send a proposal with higher price (more profit margins). In this case he knows that the probability of proposal acceptance by the CA is higher.

Based on the rank/score that obtained from bid selection procedure (see Section 6.7.1) for each CFP received from CAs, the PA assigns one of the available PMAs to the project in order to conduct bid estimation process as well as assign a weight for each project. The assigned weight will be used by MA to resolve the potential conflicts that arose where more than one PMA are competing simultaneously to gain a high scored subcontractor.

The PMA works on project specifications and prepares the contract work breakdown of the project based on different required contracts with subcontractor/trader agents (SCA). The precedence relationship between contract work breakdown items (work packages- WP) are identified and assigned to the project to form the network of the project.

The PMA sends RFBs and invites the eligible SCAs to bid on the WPs. It is worth noting that before sending the RFB, each SCA should be checked whether or not i) it gained minimum threshold score ii) its current workload is less than its capacity.

Upon receiving a RFB, a SCA checks whether or not it has enough capacity/capability to work on the bid. If the RFB sent by the PMA imposes the workload which is over the SCA's work capacity, the SCA will not bid. Those interested SCAs are able to send their bids until a certain time limit called bid termination date. Bid transfer protocol is via MS outlook and HTML files. Since the decision for sending the bid or not is made by each self-interested SCA, the PMA does not know how many bids will be collected. Therefore this could capture the real world system where some SCAs become insolvent or change their capacity level, or even change their businesses orientations as strategic decisions. In other worlds, each SCA has a "capacity" which is varied dynamically from time to time and it is determined by itself. Once an enterprise is successful in its business (e.g. KPI is high in comparison with its competitors), it could invest on its assets and increase its capacity to capture more shares from market. It is worth noting that this part of the role is a black box in the present research and could be studied in

separate research to find out how links between different layers across the supply chain can be established.

Based on the bids received from SCAs, the PMA works out the time-cost trade-off related to the project and provides the best scenarios for PA in order to raise the negotiation opportunities with CA. This process chooses the best scenario in an interactive way considering the deadline of the project (the details of this rule will be illustrated in Section 6.7.3).

The PA interactively co-operates with PMA in order to explore the best proposal for the CA. He takes into consideration the risk level of company and target price that may set by the CA to make the Bid/ no bid decision. Such expected risk level tends to be selected based upon KPI which per se is the result of the company's previous performance (the details of bid selection approach and KPI rule based strategic decisions will be explained in Section 6.7.1 and 6.7.6.1 respectively).

The PA negotiates with the CA and finally submits its proposal based on the rules and procedures that will be explained in details in Section 6.7.4 and its subsections. Final decision that is made by the CA will be revealed a certain time after the submission of the bid. If the PA's proposal is not selected, the information will be recorded and CA's project will be deactivated. The MA records the lost demand for the company. This in turn results in reduction of the reputation factor (raises the risk of company for further negotiations). This can also result in reduction of the number of future CFP announced by other potential CAs. The effect could be detected by increasing the intervals between receiving CFPs. On the other hand, if the PA is the winner of the CFP, PA will be informed by the CA and contractual agreement will be confirmed. Subsequently the MA updates the project time clock and increases the workload of selected SCAs. The available capacity of them will be announced to the other PMAs for further RFBs. In addition, the risk factors of the involved SCAs will be increased. Since the risk factor becomes updated (increases) for the collaborating SCAs and also their workload is increased, for the next projects, SCAs with higher risk factors will have less chance to be winner.

Since the PMA announces the SCAs to start their jobs based on the schedule obtained from selected point of the time-cost trade-off curve, it is responsible for making contracts with the selected SCAs. Thus, SCAs associated with the accepted bid will be informed by the PMA to start their work packages based on the schedule obtained from that particular solution of the time-cost trade-off curve (for more details please see Section 6.7.3).

During the project, progress is monitored by the PMA. In the case of a delay arising because of a particular SCA, the PMA will look at the option of changing the SCA by applying a reactive repair schedule procedure. In this process (rescheduling process) the aim is to find the appropriate SCA who is able to finish the remaining job within the remaining time window. This procedure will be explained in Section 6.7.5.

If the PMA was able to manage and complete the project on time and on budget, he will be rewarded with more credit so more projects will be given to him in the future. In addition, he will be appointed to the projects with higher complexity/uncertainty and higher budgets. On the other hand, if he was not able to manage the project, more training and monitoring approaches need to be conducted in order to increase the capability of the PMA. Again KPI of the project is utilised as feedback mechanism in order to detect the situation and provide insights in this decision making process (please see Section 6.7.6.2 for details of the proposed rule model).

Successful completion of a project increases the “reputation” of both the company and its project supply network. As it will be explained in Section 6.7.6.2, the subcontractors will be also rewarded by assigning more scores to them. This in turn increases the number of Request for Bids that they receive from company’s PMAs which means increasing the “demand” for them. This is the result of being successful in completing past projects. As successful completion of the past project is due to high collaboration between SCAs involved in the project, in order to support this collaboration for future projects, PMA tries to select collectively those SCAs that worked before with each other without any conflicts. Those SCAs have more credits with the PA and this helps towards establishment of the SCM.

However, as SCA is a self-interested agent, conducting a job perfectly will encourage him to increase the bidding price for the next RFB. It also could estimate the time of the bid more accurately because it knows the job and its experience helps him to provide better estimation.

It is worth noting that in theory, the bid estimation by SCAs who work across different tiers of supply chain can be conducted by a similar approach that the author proposed in this research. However, extending this approach to the downstream supply chain in practice was investigated based on interviews conducted with practitioners who work in lower layers of the supply chain. Although in theory the proposed model is extendable, it seems that the practitioners are not able to use the system when the size of the company and also size of the projects gets small. Therefore, the practicality of this approach in entire of the supply chain layers was questioned by the practitioners.

Looking at the general contractor (first tier company in the supply chain) for selecting SCAs, in each potential project, PMA is faced with a challenge, utilising more reliable SCAs with higher price and more accurate estimation of the job, or selecting the new SCAs with lower price and less accuracy in their job estimations. Therefore, he deals with a time-cost trade-off while he should control the risk level of the subcontractors for the new projects (see Section 6.7.2).

The PA is not only responsible for making decisions in tactical level (i.e., bid selection), but also he should detect the proper supply chain network in enterprise level. For this purpose and in conformity with DIMS (see Section 4.6, where probability clustering utilised to find the new structure) the probability clustering procedure will be conducted at the end of each year to identify the most used SCAs across the project portfolios. This in turn could be a basis toward strategic partnership agreements with those SCAs who have more collaboration in the past periods. The result would be the selection of those SCAs gradually based on these agreements. It means that the strategic objectives of the company now are aligned with the strategic objectives of the selected SCAs and thus construction supply chain gradually is configured.

Since the process is dynamic and adaptive, this structure is also dynamically changed. It means that at the end of each project PMA evaluates the performance of the SCAs and updates their scores. The KPI is also revealed by the PA. Therefore the updated data existing in the system database helps PA to adapt the supply chain by reconfiguration of the current network based on competence, capability and performance of the SCAs (for details please see Section 6.7.6 and 6.7.7).

6.7 Integrated Rule Models in proposed MAS-DSS

As it was mentioned in previous section, in this research work several rule models and functions have been utilised and integrated in order to dynamically capture the environmental situations and provide a solution that will step by step improve the enterprise situation in the market and gradually configure/reconfigure the supply chain based on lessons learned. In the following subsections the proposed integrated solution will be explained.

6.7.1 Bid/Project selection

In the construction industry as discussed in Section 2.6, project selection refers to bid selection. It means that the final decision is often made by client, so that the main contractor does not have the chance to select the projects in advance. However, the enterprise management team could decide whether or not to take part in bidding process and respond to the CFP. This is called a bid or no bid decision.

When a CFP arrives at the enterprise, there might be more than one project. Prioritising these projects and preparing appropriate bids play a critical role on the entire enterprise and its counterpart supply chain. Thus, the decision maker, the portfolio manager should make a decision in bid/no bid for the arrived CFP. Since, the knowledge of the decision maker at the early stage of each project is very poor, the uncertainty is high (see Section 1.2.4 and Figure 1.1). Therefore, risk assessment of the CFPs plays a critical role in construction industry.

As discussed in Section 2.6, Table 2.2 highlighted the models that applied in project/bid selection in the construction industry. Most frequently used methods

that are acknowledged by practitioners are those that attempt to choose the CFP with minimum risk level or choosing with higher profitability prediction. Based on observations and collected data from case study companies, it was understood that simple checklist with Likert scale approach has been used for bid selection in the large scale companies while SMEs uses simple intuition / emotional judgments made by company board of director. This findings was in compliance with (Wood & Ellis, 2003) and (Taroun, 2013).

According to the discussion in the literature review (see Section 2.6), it seems that adopting the Han et. al's model is more promising approach for bid selection which is also very similar to the current practises of the practitioners in large size case study companies (Interserve and Kayson).

Therefore, in conformity with Winter et al. (2006) and considering the practicality of the available models for practitioners, in this research, the author utilised the procedure proposed by Han et al. (2008) for risk assessment and ranking the different projects where bid and no bid decision is required.

It is worth noting that conducting several case studies revealed that small construction companies have not used such evaluation mechanism and mostly the decisions is based on CEO and member of the board intuitive judgment. Moreover, in one of the large size companies they developed an in-house model slightly similar to the Han et al.'s model i.e. there is a MADM methodology to score the potential projects, but those models were not tested academically and the validation of the models is not strong enough for the purpose of this study. So in the present research, Han et al.'s (2008) methodology is utilised to enhance MAS-DSS system with bid evaluation and risk assessment as the first step of integrated framework. The project/bid selection evaluation sheet is available in Appendix B.

It should be noted that for applying Hans et al's procedure as a subsystem of the integrated framework in the UK main contractor companies, a particular study needs to be conducted to investigate how the above mentioned score levels and decision making criteria could be modified and updated for the use in a particular company.

In brief, as this model has been academically validated, it was embedded in the integrated project portfolio management framework in order to manage the risk at the initial stage of a CFP before taking part in bidding process.

In the next step, the higher ranked projects that evaluated by the PA and his team, will be processed for bid preparation and submitting a bid with the highest existing chance for winning in the tendering process by clients. Since preparing an appropriate bid is strongly related to the subcontractor selection decisions, the latter will be illustrated in the next section.

6.7.2 Subcontractor Selection

As discussed in Chapter 2, Arslan et al.'s (2008) (WEBSES) approach was primarily adopted in this study for subcontractor evaluation. The evaluation criteria in Arslan et al.'s model can be seen in the 'Subcontractor Evaluation Sheet' in Appendix C.

However, in this study the author proposed a novel method for subcontractor selection by modifying Arslan et al.'s model in order to make it suitable for the integrated framework in which both qualitative and quantitative measurements are considered. This method consists of four steps:

- i) Scoring the subcontractors by a qualitative approach namely "Modified WEBSES"
- ii) Receiving the bids from the selected subcontractors who pass the minimum required qualitative score,
- iii) Evaluating the bids content and rejecting outliers,
- iv) Conducting a time-cost optimization to select the best combination of the subcontractors using a Time/Cost trade-off shown in a Pareto-front curve.

First, a qualitative evaluation is conducted to allocate scores. In this research the author adapted and modified WEBSES (Arslan et al., 2008) to evaluate each subcontractor on a Likert scale for time, cost, quality and adequacy calculated from their previous contract rather than taking to account their current bid. The main idea for this modification is that evaluating the quality and adequacy along with cost and time before performing a project is more subjective and it may be biased

according to the evaluator's attitudes. However after finishing a project, the evaluator could make a better judgement based on the real performance of the subcontractor. Therefore this qualitative analysis could be applied for subcontractor selection process in the next project. Moreover, a feedback of the evaluation will be transferred to the subcontractors through communication protocol which is HTTP files via MS Outlook. Therefore, all of the subcontractors who are willing to work with the company in future would be able to understand their scores. This complies with continuous improvement concepts and gives this opportunity to a particular subcontractor to improve its pitfalls and makes itself ready for the next bidding opportunity.

It is worth noting that, in WEBSES, Arslan et al. (2008) supposed that the outcome of the procedure can be used directly to select subcontractors for contracting purposes. However, in the present research after pre-evaluation of the subcontractors by the Modified WEBSES method a quantitative analysis will be conducted to select the final selected subcontractors for the project which in turn shape the project supply chain. For doing so, the final ranks/scores will be revealed for all the PMAs. This is facilitated by MAS-DSS which provide this information across all the geographically distributed projects in the portfolio. The project managers are then able to select those subcontractors with a better score and send the Request for Bid (RFB) to them. The RFB is sent electronically to the subcontractors and they have chance to compete. Their submitted bids are collected electronically through the e-mail system "MS Outlook" and directly update the database of bids.

Following the case study interview, it became clear that the users would be greatly helped if the system would assist the user by recognising the outlier bids which the user may consider deleting. This is the second step of the selection process. Those bids that are lower or higher by a certain percentage defined by the project manager (e.g. 20%) of the average price of current bids or of historical bids in the database will be identified at this stage. Therefore, at the end of this process, the project manager has a number of bids to proceed to the next stage rather than only one bid and its subcontractor. This approach allows both parts of each bid, cost and time, to be properly assessed, rather than focussing on cost and neglecting

“time” as described in (Ioannou & Awwad, 2010). In addition, although in qualitative approaches (Arslan et al., 2008), time and cost are both considered, there is no way to make a trade-off between them across the set of received bids for all of the work packages.

In the next step, a time-cost trade-off combinatorial problem is presented that is adapted for the bidding process. This model can be solved to find the Pareto-front curve which shows the optimal solutions and helps project managers, project portfolio managers and clients to compare them according to makespan and total cost of the project. This adds alternatives to the negotiations for the contractor company because they have visibility of the range of time and cost options that help clients to make their final decision. The final decision of the client and management team in selecting a solution has the effect of specifying both the general framework of the project plan and, at the same time, selecting the subcontractors. The concept of this integration is depicted in Figure 6.4.

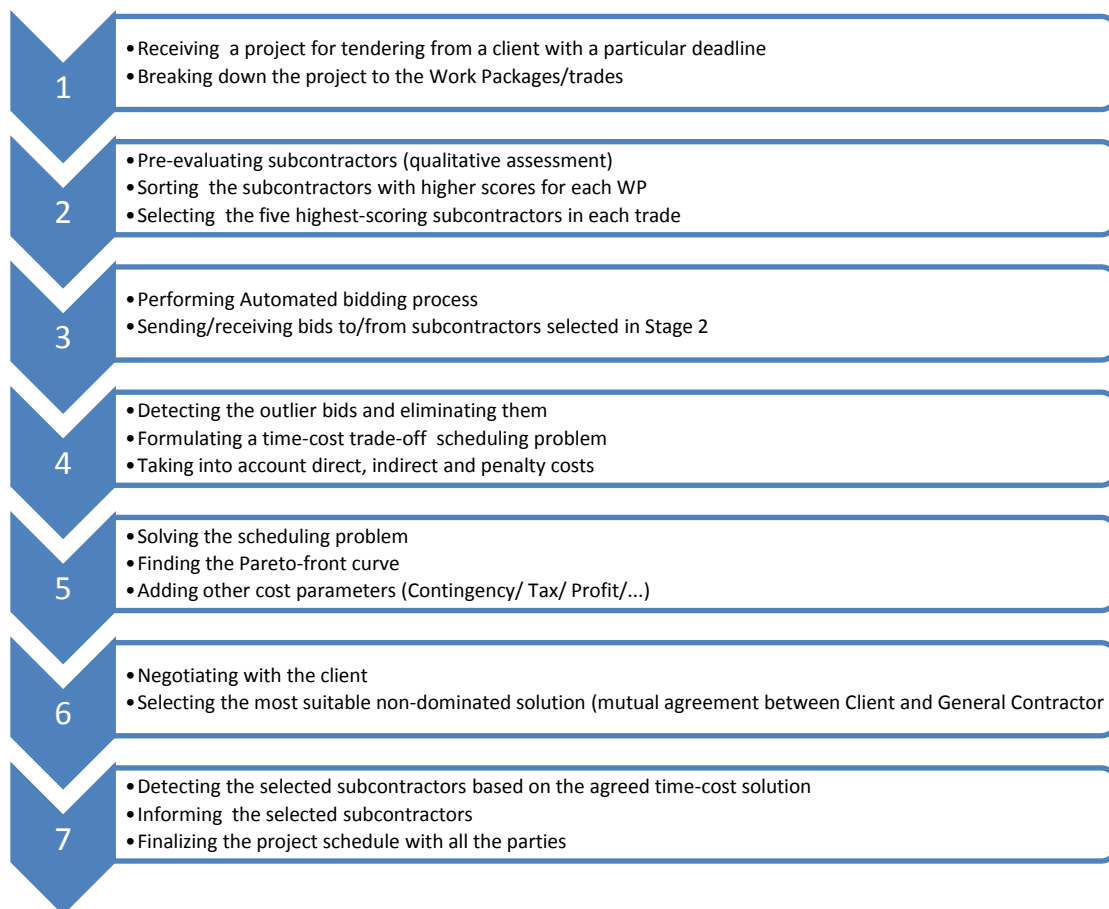


Figure 6.4 The integrated bidding process, subcontractor selection and project scheduling model

It should be noted that, since each bid that is collected from subcontractor includes time and cost of conducting the proposed work package, it will generally include a safety allowance or “padding” as contingency that subcontractor keeps it for himself as “localised protection” (Goldratt, 1997).

Yeo & Ning (2002) based on theory of constraints proposed by (Goldratt, 1997) explained, suggested that although an actor could finish a job quicker than the time that they offer in bid processing, considering “padding time” is a common approach that subcontractors used in practice. It means that the subcontractors generally submit their bids with plenty of safety time as estimated “due date”. This fact supports the idea that while preparing the baseline schedule in the adopted method; the uncertainty is implicitly taken into consideration.

It is worth noting that, E-Bidding for tendering process has been used by practitioners and studied by academics in the construction industry recently. For instance, “www.eTenders.gov.ie” has been developed as part of the Irish Government's Strategy for the Implementation of eProcurement in the Irish Public Sector” (National Procurement Service, 2013). These kinds of websites are usually developed based on an academic study carry out in the governmental organisations. For instance, Lenin (2011) proposed an Integrated E-Bidding Framework for Construction, based on the case study undertaken on Michigan Department of Transportation (MDOT). The system was orally assessed by the peers of the MDOT and showed that the focused group who were senior experts in MDOT were totally agreed with the feature of the proposed framework. Thus he claimed that the framework can be used to design electronic bidding systems for different settings in the construction industry. Therefore, according to these previous research efforts, in this study and in the third phase of Figure 6.4 an automated bidding process was proposed which facilitates communication between project managers and subcontractors based on MAS architecture that proposed in Section 6.3.

Moreover, in contrast with the current practices in the construction industry, where subcontractor selection is conducted by taking into account only cost elements of the bids (Ioannou & Awwad, 2010), or only qualitative factors such as (Arslan et al.,

2008), this method is exploiting qualitative scores of the subcontractors first and then optimising the combination of selected subcontractors to minimise time and cost of the project simultaneously. Three important factors; the subcontractor's score and the cost and time elements of each bid are considered in this model. The next section describes how a time-cost trade off problem can be utilised to achieve subcontractor selection.

In the next section the generalised discrete time-cost problem (GDTCTP) (Reyck & Herroelen, 1999), (Chassiakos & Sakellariopoulos, 2005) is adapted to suit the model to the real construction bidding situation and NSGA2 (Deb et al., 2002) is introduced to find the Pareto-front solution.

6.7.3 Project Scheduling Time-Cost Trade-off with Generalized Precedence Constraints

In order to adopting the appropriate model for project scheduling an extensive literature review was conducted and briefly presented in Chapter 3. Chapter 3 covered the literature to identify different aspects of mathematical modelling of centralised project planning and scheduling in general and in construction industry in particular. This study went further than the recent review paper in construction scheduling conducted by (Zhou et al., 2013). First, because in their study they neglected the generalised precedence constrained models. In addition, their survey did not cover multi-agent methodology and distributed multi-project planning. Therefore for this work a holistic literature review was planned to understand the models and the solution algorithms not only in traditional centralised project planning but also in decentralised models. So, the rest of the chapter 3 was devoted to the decentralised studies such as (Confessore et al., 2007), (Ren & Wang, 2011), (Arauzo et al., 2010), (Adhau et al., 2012). It also covered DIMS technology (Zhang et al., 2007) and its research line that carried out for nearly ten years in XMEC. These extensive literature reviews besides conducting in-depth case study inspired the author to adopt the appropriate model that could be fitted in the proposed integrated framework. While traditional centralised project scheduling usually focuses on single project scheduling (Zhou et al., 2013), the usage of decentralised approaches based on MAS technology and blackboard system facilitates multi-project planning in real world problems.

In this work, first a single project will be scheduled and then the resource capacity and resource load will be controlled by the blackboard system and the moderator agent.

In single project scheduling, the author adapts the mathematical formulation of GDTCTP (Chassiakos & Sakellaropoulos, 2005) and proposed multi-objective functions in order to model project master scheduling and subcontractors selection as an integrated procedure, as follows:

A linear-integer programming LP/IP formulation with existence of two objective functions is employed to explore the Pareto-Front curve. A zero-one variable x_{im} is defined for each work package (WP) to represent allocating only one winner to the job. The first objective function of the model represents the project cost and is formulated as follows:

The project start at date 0 and the deadline defined by the client is called DD.

Let TC = total cost for each single project, then from the parameters given, a mixed integer programming model for one project is given by:

$$\text{Minimise: } TC = \sum_{i=1}^N \sum_{m=1}^{B(i)} c_{im} * x_{im} + IC * f_N + P * T \quad (6.1)$$

$$\text{Minimise: } f_N \quad (6.2)$$

Where i = WP index in a project; N = is total number of WPs in a project; m = bid indicator; $B(i)$ = total number of all received bids for WP(i); c_{im} = cost of executing WP(i) based on bid m ; $x_{im} = 1$ if bid m is selected for WP(i) or 0 otherwise; IC = indirect cost of the project per day; P = penalty cost per day; I = incentive bonus; f_N = finishing time of the project; DD = client deadline of the project; and $T = \max(0, f_N - DD)$, tardiness of the project.

Eq. 6.1 represents the minimisation of the total cost of a project while Eq. 6.2 indicates the minimisation of the total time as the second objective function.

The constraints of the model are presented by the following equations:

$$\sum_{m=1}^{B(i)} x_{im} = 1, \quad \forall i \in N \quad (6.3)$$

$$f_i - s_i = \sum_{m=1}^{B(i)} d_{im} * x_{im} \geq 0, \quad \forall i \in N \quad (6.4)$$

$$s_i + SS_{ij} \leq s_j, \quad \forall (i,j) \in E_{SS} \quad (6.5)$$

$$s_i + SF_{ij} \leq f_j, \quad \forall (i,j) \in E_{SF} \quad (6.6)$$

$$f_i + FS_{ij} \leq s_j, \quad \forall (i,j) \in E_{FS} \quad (6.7)$$

$$f_i + FF_{ij} \leq f_j, \quad \forall (i,j) \in E_{FF} \quad (6.8)$$

$$f_N \geq f_i, \quad \forall i \in N \quad (6.9)$$

$$s_i \geq 0, \quad \forall i \in N \quad (6.10)$$

$$s_0 = 0 \quad (6.11)$$

where f_i =finish time of WP (i), s_i =start time of WP (i), d_{im} = duration of WP (i) based on bid m, j = successor WP to WP(i) in a project ; SS_{ij} = time lead/lag between start of WP(i) and start of WP(j), E_{SS} =set of SS precedence relation, SF_{ij} = time lead/lag between start of WP (i) and finish of WP(j); E_{SF} =set of SF precedence relation, FS_{ij} = time lead/lag between finish of WP(i) and start of WP(j); E_{FS} = set of FS precedence relation, FF_{ij} = time lead/lag between finish of WP(i) and finish of WP(j); E_{FF} = set of FF precedence relation.

Eq. 6.3 ensures that each WP will be assigned to only one subcontractor among all received bids. Eq. 6.4 relates start and finishing time of each WP (i) to the selected bid. Eqs. 6.5-6.8 indicate the time lag/lead between activities in the project. Eqs. 6.9-6.11 set the start and finish time of the each WP(i).

It is obviously that in portfolio there are a number of projects each of which could be modelled as above. However, in the real dynamic world we do not know how many Calls for Proposals (CFP) from the clients will be proposed to the portfolio. Furthermore, although project portfolio manager makes a decision for bid/no-bid decision, even after submitting the bid he does not know whether or not the proposed bid will be chosen by the client. Moreover, projects are scattered across geographical areas. Thus the project interdependency between the projects arises when the different project managers may send the RFB to the subcontractors at the same time, however it is not clear whether or not a subcontractor should be allocated to the more than one project at the same time. In a very special case, suppose that two proposals submitted to the different clients and both will be

accepted. If both projects select the same subcontractor, then the capacity of the subcontractor would be less than the required capacity. This causes a conflict.

Since the Moderator Agent responsible for updating and controlling the overall performance of the system is in charge of all the data in the blackboard, this conflict will be detected in the multi agent system platform. Therefore, MA will not allow the PMAs to allocate workloads to the subcontractors over their pre-evaluated capacities. This conflict has been resolved by considering the priority weight that has given to the projects by the portfolio manager in strategic decision layer.

It worth noting that, since that interdependency between construction projects is low while uncertainty and variability of each of them are high; therefore, regarding resource planning -subcontractor allocation - the only existing constraint would be capacity and limitations of deploying them concurrently in several projects which cause their load to exceed their capacity. As discussed in architecture of the proposed system, the blackboard system monitors the capacity and load of each subcontractor. It is able to manage over loading of an individual subcontractor who is willing to put forward several bids and takes part in several projects with even different project managers who are geographically dispersed. It means that when a subcontractor is appointed to a particular project, the system checks its capacity and its allocated loads while its risk score will be increased result in reducing the chance of being the winner in the next bidding process.

In addition, if there would be a conflict for allocating a particular subcontractor to more than one project simultaneously, there is a mechanism in the proposed architecture that facilitates prioritising the projects for resource allocation.

Moreover, the capacity of subcontractors will be evaluated and updated periodically by the project managers. Thus unlike the other research works in the literature, this works could be counted as dynamic supply chain in which number of subcontractors are varied time by time and also their capacity should be examined regularly. The agent based system proposed in this study facilitates these interactions between agents and makes the framework closer to the real dynamic

complex system. This in turn makes the integrated system more suitable for practitioners.

In the following subsection, NSGA2 will be adopted to find the solution for the mathematical model.

6.7.3.1 Solution algorithm

The time cost trade-off problem (TCTP) has been addressed for many years. While some scholars provided mathematical programming models such as dynamic programming, linear programming and integer programming LP/IP hybrid, there is an argument that these methods cannot efficiently obtain optimal solutions for large-scale networks (Feng et al., 1997). In addition they may easily get trapped into local optima (Zheng, 2004). Because of these drawbacks of exact solution approaches, many scholars use heuristic and metaheuristic algorithms such as tabu search approach and genetic algorithms (GA). A comprehensive survey of different approaches to single objective TCTP is presented in (Węglarz et al., 2011).

There is also a large amount of work using bio-inspired approaches in which minimization of both cost and time as two objective functions are considered. These include Ant Colony optimization (ANC) (Xiong & Kuang, 2008), Particle Swarm Optimization (PSO) (Yang, 2007) and Harmony Search (HS) optimization (Geem, 2009) methods. These have been applied to gain the optimal Pareto-set solution. The multi objective genetic algorithm is one of the most applied methods in the literature (Feng et al., 1997), (Zheng, 2004), (Ghoddousi et al., 2013). However, only a few studies in the field of time cost trade off problem take into account the generalised precedence relationship (GDTCTP) between activities (Chassiakos & Sakellariopoulos, 2005), (Sakellariopoulos & Chassiakos, 2004), (Hebert & Deckro, 2011).

According to the analysis conducted in Chapter 4, Section 4.8, in this research, the author compared 'iterative bidding process' introduced in DIMS to NSGA2 as two viable methodologies that can be utilised in a multi agent system framework to solve the DTCTP. The results showed that NSGA2 is faster and is able to provide better solutions. In the same vein, in order to tackle the GDTCTP in this research

NSGA2 is utilised to achieve Pareto-front solution for the problem GPTCTP that used for modelling subcontractor selection and project scheduling simultaneously. NSGA2 is used to develop a Pareto-front curve that shows the best compromising solutions between cost and time. In the construction scheduling problem model proposed in this study, each WP is allocated to one subcontractor/trader, and as in Feng et al., (1997) the chromosome has been defined in such a way that it represents the possibility of allocating different eligible subcontractors to each WP. It should be noted that according to the analysis conducted in Section 4.8, the NSGA2 can be utilised in a multi agent system framework as the optimisation tool.

In order to verify the model and the adopted solution algorithm i.e. NSGA2, the case study data taken from the construction project of three accommodation blocks at the University of Exeter (please see Section 5.2.2) was used. The results were compared with the current practices through presentation and discussions with the project management team of UPP. The results were highly acknowledged by the practitioners as will be discussed in Chapter 7. Owing to the confidential circumstances which are related to the bidding information, the author is unable to provide any details of the information and its corresponding results (please see Section 7.3 for more explanation where the prototype MAS-DSS solution software will be presented).

However, in this section, a numerical example of GDTCTP with 29 activities was chosen from Sakellaropoulos & Chassiakos (2004). As discussed in Section 3.2.2.1, their proposed mathematical model is based on a single objective function. The project activities and their generalised precedence relationships are shown in Table 6.1 and the time cost options are presented in Table 6.2. The test case data was implemented in a spreadsheet model and SolveXL NSGA2 optimiser (Savić et al., 2011) as described previously in Section 4.8.2 was utilised to provide a Pareto front. The results of the proposed model in this research were compared with the obtained solutions by Sakellaropoulos & Chassiakos (2004) that solved the problem using Lindo software, release 6.01.

Table 6.1 Project activities and precedence relationships			Table 6.2 Alternative activity time cost options						
Activity no.	Activity description	Precedence relations	Activity no.	Option 1		Option 2		Option 3	
				Time	Cost	Time	Cost	Time	Cost
<i>Service road A</i>			1	5	2030	4	2300	–	–
1	Rock excavation	–	2	8	1020	7	1280	6	1510
2	Embankment construction	1FS – 3	3	8	1700	7	1850	6	2090
3	Subbase and base layers	1FS, 2FS	4	4	590	3	730	–	–
4	Asphalt layer	3FS	5	2	90	–	–	–	–
5	Temporary marking and signing	4SS + 1	6	4	910	3	1100	–	–
<i>Service road B</i>			7	2	250	–	–	–	–
6	Earth and semi-rock excavation	1FS	8	7	1490	6	1650	5	1830
7	Embankment construction	2FS, 6FS – 1	9	4	520	3	750	–	–
8	Subbase and base layers	3FS, 7FS	10	2	90	–	–	–	–
9	Asphalt layer	4FS, 8FS	11	1	50	–	–	–	–
10	Temporary marking and signing	5FS, 9FP + 1	12	8	3260	7	3580	6	3710
<i>Main road</i>			13	5	1140	4	1400	3	1720
11	Traffic diversion	5FS, 10FS	14	4	300	3	450	–	–
12	Rock excavation	11FS	15	8	1020	6	1300	5	1430
13	Earth and semi-rock excavation—existing pavement removal	12SS + 2	16	9	790	8	900	6	1180
14	Subgrade stabilisation, retaining wall/culvert construction	13SS + 2	17	13	3340	12	3750	11	4060
15	Embankment construction	12FS – 4, 14FS – 2	18	9	470	8	650	7	830
16	Drainage pipe construction	15FS – 6	19	6	460	5	600	4	810
17	Drainage layer	15SS + 4	20	6	1280	5	1430	–	–
18	Planting at roadway verges	15FS + 4	21	14	1090	12	1320	10	1560
19	Electrical installations at roadway verges	15FS	22	14	900	11	1140	9	1400
20	Ditches	17SS + 3	23	14	2220	12	2510	11	2690
21	Subbase layer	20SS + 2	24	3	230	–	–	–	–
22	Base layer	21SS + 2	25	6	1590	5	1790	4	1990
23	Median island (New Jersey)	22FS – 9	26	10	2630	9	2930	8	3240
24	Electrical installations in median island	23SS + 6	27	8	2060	7	2450	6	2660
25	Asphalt layer #1	23FS – 4	28	10	320	9	440	8	610
26	Asphalt layer #2	25SS + 4	29	1	50	–	–	–	–
27	Friction course overlay	26FS							
28	Final marking and signing	27FS – 3							
29	Traffic restoration	28FS							

The indirect project cost= 150 units per day.
The penalty cost= 200 units per day of delay applies after the 80th day.
The bonus (negative) cost= 100 units per day is given for project completion before the 80th day.

The obtained solutions by exact algorithm using Lindo software is shown in Table 6.3. As shown in Table 6.4, the obtained solution using NSGA2, based on the multi objective modelling formulation proposed in this research, are similar to the exact solutions. The Pareto-front solutions are presented in Figure 6.5. The solutions with time less than 76 are dominated solutions therefore they were eliminated in NSGA2. Moreover, using SolveXL enables the project managers to easily implement the activity precedence relationships and achieve the project schedule for each of the obtained solutions from the NSGA2 algorithm. For instance, Figure 6.6 shows the project schedule for the cheapest option i.e. 45500 where the duration is 75.

**Table 6.3 Solutions obtained by exact algorithm
Sakellaropoulos & Chassiakos (2004)**

Project duration	Direct project cost	Indirect project cost	Direct + indirect project cost	Penalty/ bonus	Total project cost
93	31,890	13,950	45,840	+2600	48,440
92	32,010	13,800	45,810	+2400	48,210
91	32,130	13,650	45,780	+2200	47,980
90	32,130	13,500	45,630	+2000	47,630
89	32,250	13,350	45,600	+1800	47,400
88	32,390	13,200	45,590	+1600	47,190
87	32,510	13,050	45,560	+1400	46,960
86	32,660	12,900	45,560	+1200	46,760
85	32,800	12,750	45,550	+1000	46,550
84	32,950	12,600	45,550	+800	46,350
83	33,100	12,450	45,550	+600	46,150
82	33,260	12,300	45,560	+400	45,960
81	33,430	12,150	45,580	+200	45,780
80	33,610	12,000	45,610	0	45,610
79	33,790	11,850	45,640	-100	45,540
78	34,020	11,700	45,720	-200	45,520
77	34,260	11,550	45,810	-300	45,510
76	34,510	11,400	45,910	-400	45,510
75	34,750	11,250	46,000	-500	45,500
74	35,020	11,100	46,120	-600	45,520
73	35,320	10,950	46,270	-700	45,570
72	35,620	10,800	46,420	-800	45,620
71	35,920	10,650	46,570	-900	45,670
70	36,230	10,500	46,730	-1000	45,730
69	-	-	-	-	-

Figure 6.5 Pareto-front solutions obtained by NSGA2

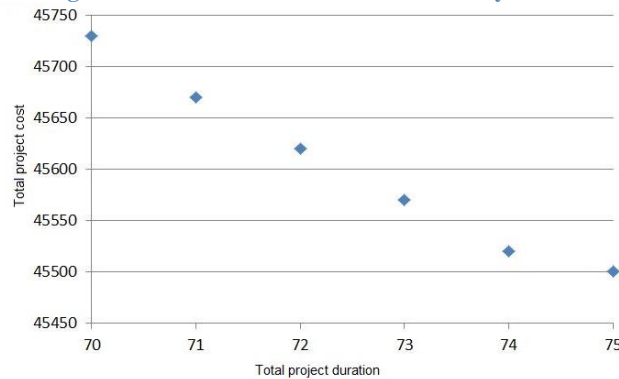


Table 6.4 Solutions obtained by NSGA2

Activity no.	Solution ID no.					
	19	20	22	24	35	50
1	2	2	2	2	2	1
2	3	3	3	3	3	3
3	3	3	3	3	3	3
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	1	1	1	1
8	3	3	3	3	3	3
9	2	2	2	2	2	2
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12	1	1	1	1	1	1
13	1	1	1	1	1	1
14	2	2	2	2	2	2
15	1	1	1	1	1	1
16	1	1	1	1	1	1
17	1	1	1	1	1	1
18	1	1	1	1	1	1
19	1	1	1	1	1	1
20	1	1	1	1	1	1
21	1	1	1	1	1	1
22	3	3	3	3	3	3
23	3	3	3	3	3	3
24	1	1	1	1	1	1
25	1	1	1	1	1	1
26	3	2	1	2	1	1
27	3	3	3	1	1	1
28	3	3	3	3	3	3
29	1	1	1	1	1	1
Project duration	70	71	72	73	74	75
Total project Cost	45730	45670	45620	45570	45520	45500

There are only six non-dominated solutions.

As it is shown, the outcome of the NSGA2 is a set of non-dominated solutions which are trade-offs between time and cost of accomplishing a project. Each solution is a combination of a set of subcontractors that PMA could be able to perform the project by collaboration with them and deliver the project with a specific makespan and a certain amount of cost. These solutions can be negotiated with the client in order to achieve the best result. [This in turn will](#)

increase the competitiveness of the general contractor compared with his rivals.

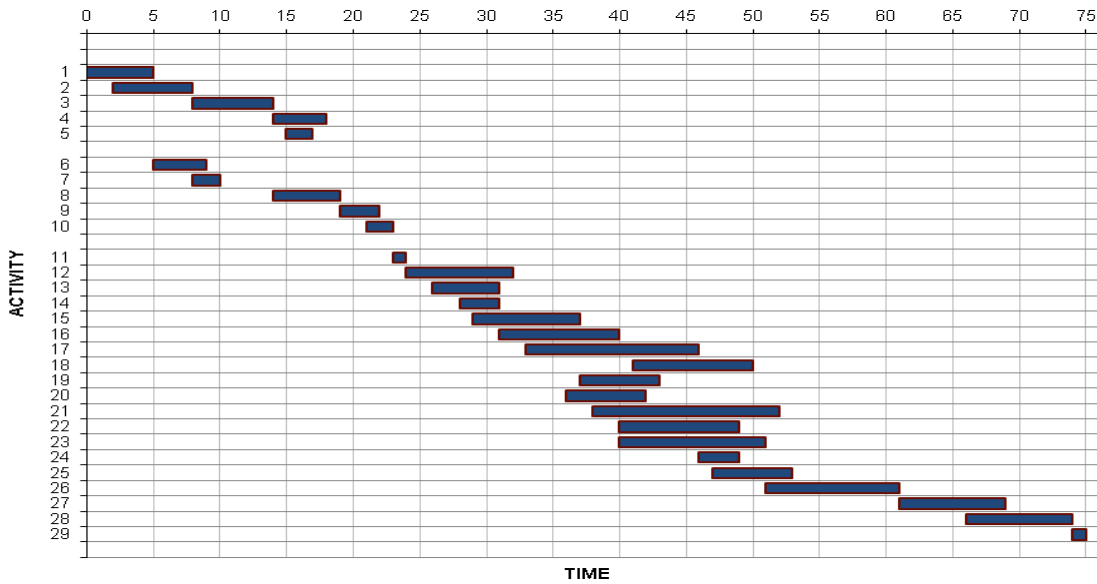


Figure 6.6 Project schedule (for project duration 75, project total cost 45500)

In the current research, the author proposed two different methods that will be utilised for bid preparation decisions and negotiation with the client.

6.7.4 Bid preparation decisions and negotiation with client agent

As discussed earlier, the final bid that is being prepared for the client should be strong enough to convince the client to select the enterprise compared with the competitors. Moreover, proposing a good proposal with high chance of success / minimum risk, helps to establish the project contract and continuation of the work with its supply network. Thus it could be seen as the linkage between operational decisions and strategic decisions so this kind of procedure can be categorised as a tactical decision. As discussed in Section 6.7.1, although project/bid risk ranking has been utilised in the holistic framework and its associated MAS-DSS, the next step is how PA should prepare the reliable bid in order to raise the chance of winning in competitive market.

In current practices, bid preparation is a very time consuming job and usually is made in a central way. It means that PA's team is responsible for this exhaustive job. They should estimate the bid price and prepare the bid in order to submit the proposal in a very short time usually between 2-6 weeks (Laryea & Hughes, 2008). The price of the bid is estimated by "direct construction cost including field

supervision, plus a mark-up to cover general overhead and profits. The direct cost of construction for bid estimates is usually derived from a combination of the following approaches, Subcontractor quotations; Quantity take-offs; Construction procedures” (Zavadskas et al., 2008). Conducting the case study also revealed that in current practice the contractor just offers one price to the client. Hence, the client should select the most desirable received proposals from several competitors in a tender process.

In the model proposed in this research, two scenarios for the rest of the procedure were investigated. These alternative approaches tend to increase the capability of negotiation with client resulting in raising the chance of winning the tender. Given a set of solutions based on time and cost trade off, the contractor is then able to offer a range of project delivery dates to the client. These two possibilities for submitting the proposal to the client are based on the tendering conditions when:

- i) The CFP is negotiable.
- ii) The CFP is based on competitive bidding.

In this research both conditions will be supported by appropriate procedures that were utilised by the proposed MAS-DSS. In the next two subsections they are illustrated.

6.7.4.1 Negotiable Call for Proposals

In the construction business environment, when the enterprise has a good enough reputation, it is usually invited to the negotiation process by clients. As discussed, KPIs are the main important parameters in which contractor can benchmark the market and understand its position within the market. Higher KPI means that the position of company in the market is good and thus has a higher reputation, fewer competitors, less risk in losing the market, a higher chance to win the bid, and finally has more clients and CFP per year.

In this case, with regards to each CFP, PA has a range of solution obtained by MOGA in Section 6.7.3.1 for negotiation with client. When the total budget has been announced by the CA, PA works out to examine how much profit margin can be obtained based on the non-dominated solutions computed by the NSGA2.

Therefore, PA can negotiate with CA to achieve a mutual agreement. However, rather than negotiating with CA directly based on non-dominated solutions, there is another possibility that I proposed in this research in order to facilitate decision making for both sides of the negotiation process, i.e. portfolio manager and client as follows. The idea is derived from the research conducted by Wallenius et al. (2008) when they introduced the research directions in multi criteria decision making (MCDM) and multi attribute utility theory (MAUT) research agenda. They referred to the research work conducted by Teich et al. (2004) and explained how the real business environment can use the MAUT in e-auction process to come up with a decision making.

This idea is brought into the proposed multi agent system to facilitate the negotiation process where negotiation is taken place between PA and CA. In this model, although PA is responsible for communicating and negotiating with the CA for terms and conditions of the proposal, he benefits from the efforts that made by PMA. Therefore, responsibility is shared and the process could speed up. Looking at the Pareto-front curve obtained by PMA, he can open a negotiation with CA based on the multi agent platform that was presented in Figure 6.2. In this procedure, PA asks CA to give him weights with regards to different attributes (x_j) such as:

x_1 - construction duration [months].

x_2 - bid estimates [million GBP].

x_3 - guarantee period for screen works [year], must be not less than 10 years.

x_4 - guarantee period for finishing works [year], must be not less than 5 years.

These guarantees are concerned with contractor responsibility for the quality workmanship, the quality of the materials used, and for performance of the contract only. In the literature, there are some more attributes that can be seen, e.g. (Zavadskas et al., 2008), however, after discussion with PMAs in the case study company regarding the practicality they were happy with these more important attributes.

After receiving an enquiry about the preferences of the client pertaining to the above mentioned attributes, the CA informs the PA about his preferences by giving weights to the attributes. This data transferring can be easily handled by the proposed MAS-DSS architecture where Microsoft outlook and HTML pages was utilised for send and receiving information between PA and CAs.

The PA can use the multi attribute utility theory to find out which of the Pareto front solutions are more attractive for the CA. Thus he would suggest the ranked choices across the all non-dominated options to the CA. This increases the negotiation quality and the chance of winning the CFP in compare with other competitors, which in turn it would affect the continuation of the supply chain operation.

For illustration of the method, assume that the PMA has conducted a time cost trade-off analysis using NSGA2 and has provided a set of 10 solutions to the PA (see Section 4.8, particularly Table 4.6 and Figure 4.7). According to the tendering specifications, two more attributes need to be considered for the bid submission. These are, for example, the guarantee periods for screen works and finishing works. The PA has worked out on the bid and has 10 different alternatives for negotiation with the CA as shown in Table 6.5. In this table, the first three columns are the solutions obtained by the PMA using NSGA2 and the two last columns are considered by the PA based on tendering requirements. Considering this alternatives, he/she can directly negotiate with the CA. Nevertheless according the method proposed in this study, the PA made an inquiry from the CA about its preference/utility/weight of each attribute. Suppose that the CA has replied to the PA's inquiry and announced the weights for project duration, project total cost, guarantee period for screen works and guarantee period for finishing works, 0.35, 0.25, 0.15 and 0.25 respectively which can be seen in Table 6.5.

In this table, it can be seen in the "Nature" row that the first two attributes (time and cost) should be minimised and the two others (guarantee periods) are to be maximised. Thus by using the linear normalization technique (Zavadskas et al., 2008) the normalised table (Table 6.6) can be obtained:

$$\bar{x}_{ij} = \frac{x_{ij} - \min_j x_{ij}}{\max_j x_{ij} - \min_j x_{ij}} \quad \text{when } \max x_j \text{ is optimal,} \quad (6.12)$$

$$\bar{x}_{ij} = \frac{\max_j x_{ij} - x_{ij}}{\max_j x_{ij} - \min_j x_{ij}} \quad \text{when } \min x_j \text{ is optimal,} \quad (6.13)$$

Where \bar{x}_{ij} is normalised value of the original x_{ij} value. (i indicates alternative index and j indicates the attribute index).

Table 6.5 Non-dominated solutions and guarantee periods set by the PA

Solutions	total time	total cost	Guarantee period for (GPF)	
			screen works	finishing works
Nature	Min	Min	Max	Max
Weight	0.35	0.25	0.15	0.25
S1	34	1846	2	45
S2	37	1834	2	45
S3	41	1826	5	30
S4	46	1824	5	30
S5	51	1820	5	30
S6	64	1782	5	45
S7	67	1770	5	45
S8	71	1762	3	45
S9	77	1755	3	30
S10	81	1747	3	20

The utility function can be written as follows:

$$K_i = \sum_{j=0}^n w_j \bar{x}_{ij} \quad (6.14)$$

Where w_j is the assigned weight of each attribute (by CA) and K_i is the utility value of the i_{th} alternative.

After applying the utility function, the best option for the CA is solution S7 with the highest utility equal to 0.371. This means that client is more willing to make a contract if the bids parameters would be: time = 67 month, cost = 1770 cost units, GPF screen work= 5 years and GPF finishing works = 45 years). Thus, based on the present agent architecture, the PA could evaluate the rankings and apply them in the negotiation process.

Although MAUT facilitates decision making that should be conducted by the client agent, the last decision still is unknown for PA. CA compares all the received proposals from several other competitors and finally announces the result. Since

the preference of the client is taken into consideration prior to sending the proposal, it is expected that the chance to be winner would be higher than other competitors.

Table 6.6 Ranked solutions for negotiation purpose based on CA’s preference

Solutions	total time	total cost	GPF screen works	GPF finishing works	Ranked Solutions
S7	0.30	0.77	1.00	1.00	0.371
S6	0.36	0.65	1.00	1.00	0.366
S3	0.85	0.20	1.00	0.40	0.337
S4	0.74	0.22	1.00	0.40	0.321
S5	0.64	0.26	1.00	0.40	0.308
S8	0.21	0.85	0.33	1.00	0.287
S2	0.94	0.12	0.00	1.00	0.275
S1	1.00	0.00	0.00	1.00	0.270
S9	0.09	0.92	0.33	0.40	0.220
S10	0.00	1.00	0.33	0.00	0.180

However, the situation is more risky when the CFP is competitive and negotiation is not allowed before bid submission. The next section is concerned with this case.

6.7.4.2 Call For Proposal based on competitive bidding

When the reputation of the enterprise and also trust between general contractor and client is not so strong to stimulate client into choosing the negotiated contract, competitive bidding is announced by the client. In this case, the PA should prepare an accurate bid that helps the chance of winning in bidding process.

As negotiations are not allowed, the PA does not know what the preferred weights/ utility preferences of the CA are (discussed in the previous section). Thus he should make a guess and estimate parameters based on his previous knowledge (possibly from previous records from that particular client). Therefore, the PA must accommodate this uncertainty and risk based on his/her previous background knowledge from the market situation and tries to guess the client preferences. This kind of uncertainty and risk refers to ambiguity or ambiguous risk. Generally, decision problems with unknown probabilities are said to be ambiguous (Eichberger & Kelsey, 2007).

For dealing with this decision making situation the Hodge-Lehmann rule is adopted (Hodges & Lehmann, 1952). In this rule, the decision maker has limited knowledge

based on his/her experience to estimate the utility weights of the client associated with time, cost and guaranteed time spans (see table Table 6.5). In other words, because he has directly collected utility preferences from client, he has 100% confidence in this data so that he can use the previous rule (see Section 6.7.4.1). However, in the competitive bidding process, as negotiation is not allowed he can only estimate the weights. In this case, since the market is very tough and competitive, he does not like to lose the potential project. Therefore he could not directly use the procedure that explained in previous section. Instead, in multi criteria decision making “maximin” approach is used when the decision maker (PA) is risk averse and there is not any confidence (0%) to the allocated parameters. It is also named ambiguity-aversion (Eichberger & Kelsey, 2007).

Hodge-Lehmann showed that when there is a certain risk level to the knowledge perceived from previous experiences (or let say the decision maker could tolerate ρ level of risk), the best decision could be obtained by using following formula:

$$K_i = \rho \sum_{j=0}^n q_j \bar{x}_{ij} + (1 - \rho) \min_j \bar{x}_{ij} \quad (6.15)$$

$$K_{opt} = \max_i K_i \quad (6.16)$$

where q_j is weight that estimated by PA’s experience/knowledge (not directly obtained by client), K_i is optimality criterion, and K_{opt} is optimal alternative.

This rule was applied in the multi agent system to help PA makes a better decision when he wants to prepare and send a bid to the CA. Applying the method in the previous example, results in the following table (Table 6.7).

Table 6.7 The best decision based on risk level

Confidence level	0	0.25	0.5	0.75	1
Max Score	0.36	0.36	0.36	0.36	0.37
The best alternative	S6	S6	S6	S6	S7

As can be seen, when the PA has 100% confidence to his knowledge i.e. $q_j = w_j$ the result is similar to the previous case (S7), otherwise the best selection would be alternative solution S6 from the main table. Therefore, the best pitch that PA could submit to the CA is S6: (time= 64, cost= 1782).

As discussed, this method supports decision making in tendering process when PA should submit the final bid in competitive market with limited knowledge about the

market situation and client's orientations toward time and cost of the delivery of a project.

All the required rules and procedures that are associated with the PA making decisions and negotiating with CA in the multi agent system have been presented. However, the final decision regarding appointing the company to the project is unknown and beyond the control of the general contractor. These rules support the general contractor in undertaking better tendering process and submitting the final bid with a higher chance to win.

In the next step, rescheduling procedure will be illustrated.

6.7.5 Rescheduling negotiation protocol

Assuming that the company achieved the contract and started the project, project manager agent should schedule the project and announce the subcontractors to start the job based on the agreed plan discussed in Section 6.7.3. In this case, the PMA is responsible for monitoring the progress of the project and checking progress against the milestone achievements by each subcontractor. As discussed in Section 4.3 the best approach for rescheduling the construction industry is the repairing approach.

According to the interview and findings from case studies, it is revealed that in this case the aim is not minimizing the cost but the proper subcontractor should be selected so that the turbulence should be minimised. This part reflects the proposed procedure and negotiation approach between PMA and SCA based on theoretical background discussed in Section 4.3.2. Figure 6.7 shows the proposed rescheduling negotiation protocol.

The procedure is started whenever PMA detects a SCA is no longer able to carry on the allocated work package (WP). PMA calculates the remaining work (R) and check whether there are any submitted bids for the job previously or not. If there are some bids available for the original job from one or some SCAs, the priority is given to those with minimum cost where the duration of the bid (D) is less than the remaining time of the baseline schedule. Therefore, an invitation for the job will be sent to the SCA and waits for its response. Obviously, if the SCA has available capacity, it will accept the invitation and the reschedule will be conducted without

any turbulence. The MA updates the blackboard in terms of score, remaining capacity and workloads of the SCA.

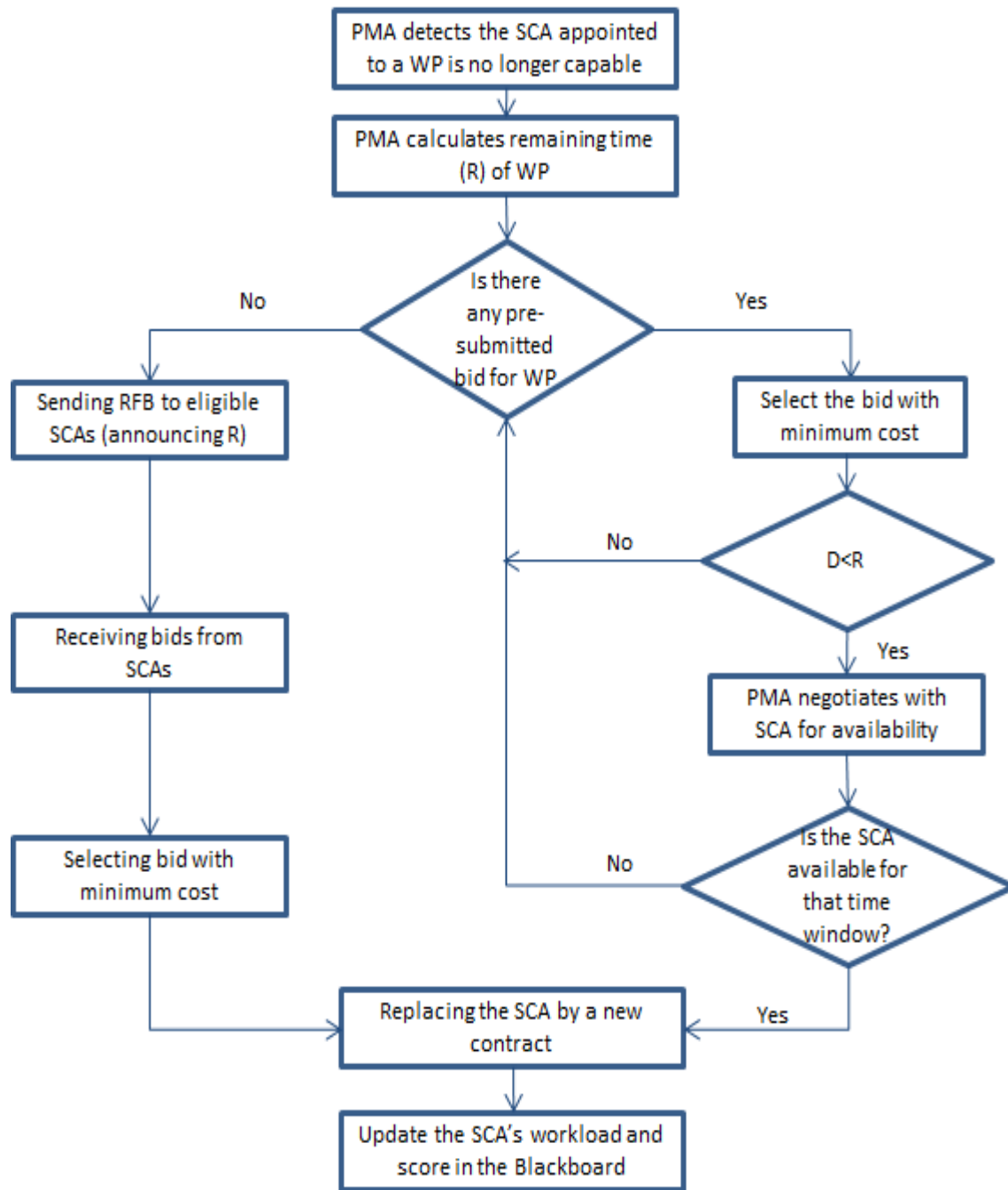


Figure 6.7 Rescheduling negotiation protocol

However, if there are not any available submitted bids for that particular job, PMA needs to manage a new bidding process for the remaining job. A RFB will be sent to and received from eligible SCAs whose score is upper than the acceptable level. Since in this case the objective is minimising the turbulence in the baseline

schedule, the PMA will send the RFB and ask for the cost to complete by the required date. Therefore, the SCAs will compete with each other just based on cost estimation. Thus the minimum turbulence will be seen across the project schedule. In the next sections, remaining rule procedures that are governed collaboratively by KPI benchmark agent, bid selector agent and supply chain configurator agent will be explained.

6.7.6 KPI Rule models

As discussed in Sections 6.2-6.4, in this research KPI benchmarking is used to compare the situation of the enterprise with other competitors in the market. As briefly mentioned in Chapter 4, the investigation of KPI measurements are out of the scope of this work. Instead, in the proposed integrated hierarchical framework discussed in Section 6.2, this study aims to focus on the usage of them to support making the strategic decisions for the future as (“lessons learned”). This would be similar to the research work that uses SCOR model for benchmarking the performance of the dynamic supply chain proposed by Persson & Araldi (2009), however, to the best of the author’s knowledge there is not any research for addressing the integration of KPI Engine & Zone with the enterprise’s data source in the field of dynamic construction supply chain management.

According to the literature, Multi Agent System can be utilised in order to integrate the internal database with external data obtained from websites using an ontology-based approach (Soo et al., 2006), (Lavbič et al., 2010), (Shirabad et al., 2012). Particularly, Lavbič et al., (2010) used ontologies for integration of information. In their proposed MAS-DSS, agents can use both internal data and also information obtained from external websites. They also emphasised on using business rules which new knowledge can be inferred to support decision making. They tested and verified their methodology in the mobile market industry.

In this research, the presented platform can be utilised to integrate data across the project portfolio and other data sources such as KPI Engine & Zone. Thus, similar to Lavbič et al.’s method, KPI Benchmark Agent introduced in Section 6.3 can integrate the MAS-DSS’s database with KPI Engine & Zone website so that relevant data i.e. KPIs are reported to PA and according to predefined portfolio

manager's rules tactical and strategic decisions can be made (see the following Subsections).

The communication protocol discussed in Section 6.5 facilitates data collection from different physical business agents, internal and external, including the portfolio manager, project managers, clients and subcontractors. It means that, after finishing each project, KPI benchmark agent sends required questionnaires to the relevant parties, for instance the client and then receives the information from the client in order to calculate customer satisfaction KPI.

Therefore, in this research the methodology for calculating the KPIs in KPI Engine & Zone is adopted in order to take advantages of benchmarking from this platform (Centre for Construction Innovation, 2013). Those KPIs that are calculated based on CCI's methodology (were applied in KPI Engine & Zone) are used to support the enterprise decisions. These will be used for determining the tactical and strategic decisions. Bid/project selection as a tactical decision and supply chain configuration as a strategic decision are both influenced by relevant KPIs when benchmarking is used to compare with other competitors in the market.

This is in conformity with aligning the strategic management and performance measurement systems discussed by Price (2003) and Bassioni et al. (2005). Therefore in this research, the proposed MAS architecture facilitates aligning KPI management with strategic and tactical decisions. These can be integrated so that the top management team including the Portfolio Manager and the Project Managers collaboratively achieve this goal.

KPI Benchmark agent communicates with KPI Engine & Zone website in order to transfer required information for benchmarking KPIs at the end of each project. It is also responsible for handling KPI's rule models to support decision making in enterprise level. Therefore, by writing and reading information from this website, KPI benchmark agent is able to support enterprise's tactical and strategic decisions based on the pre-set business rules. These rules will be set by portfolio manager by relevant user interfaces. In two next subsections, two rule models will be described.

6.7.6.1 KPI control rules for Bid/Project selection


Referring to hierarchical integrated project portfolio framework discussed in Section 6.2, as the proposed framework has been established based on multi agent architecture it is able to integrate different decision levels of the hierarchy.

In conformity with the approach of Lavbič et al. (2010) and Piramuthu (2005), in this section a table of business rules is introduced so that the business user, i.e. the PA, can set rules in MAS-DSS. These rules are used by the agent to support decision making at the tactical level of the hierarchy where bid/project selection is in line with tendering process and consequently initiate subcontractor selection. It means that, when the KPI benchmark agent calculates Customer Satisfaction KPI and compares it with Construction Industry's KPI, different decisions could be made to support the business.

Since the portfolio manager is responsible for strategic and tactical decisions, in the proposed system architecture, there are mechanisms suggested to handle and support these decisions. For instance, with respect to KPI benchmarking, these decisions are included to increase or decrease the number of concurrent projects across the portfolio as well as changing the profit margin for tendering process for the upcoming call for proposals (CFPs). In Table 6.8 the suggested business rules are shown however, in the MAS-DSS they might be altered by the user i.e. PA, through a user interface.

Table 6.8 Customer satisfaction KPI and Business rules set in MAS-DSS for Bid selection

Suggested rules can be set in MAS-DSS		
KPI: Customer Satisfaction	Change in Number of active projects	Change in Profit margin
>10+	15% ↑	3-4% ↑
+10%	10-15% ↑	2-3% ↑
+5%	0-10% ↑	1-2% ↑
-5%	0-10% ↓	1-2% ↓
-10%	10-15% ↓	2-3% ↓
-10%<	15% ↓	3-4% ↓



These rules are set in line with the enterprise capacities for handling concurrent projects and also the profitability of the company. So “KPI for client satisfaction with the product” (Centre for Construction Innovation, 2013) is used to control the number of active projects as well as controlling the profit margins based on performances of the PA and PMA in previous projects. Thus the concept of continuous improvement can be implemented for system adaptation.

Integrated MAS-DSS can handle and control all the parameters across the different sub-systems. In other words, KPI benchmark agent updates the blackboard of the system through the MA and MA uses updated parameters to control number of concurrent project across the system. Furthermore, when PA prepares tender package based on the procedures discussed in Section 6.7.4, the system supports decision making for choosing profit margin which is based on feedback achieved from KPI benchmarking that reflects the reputation of the business in comparison with other rivals.

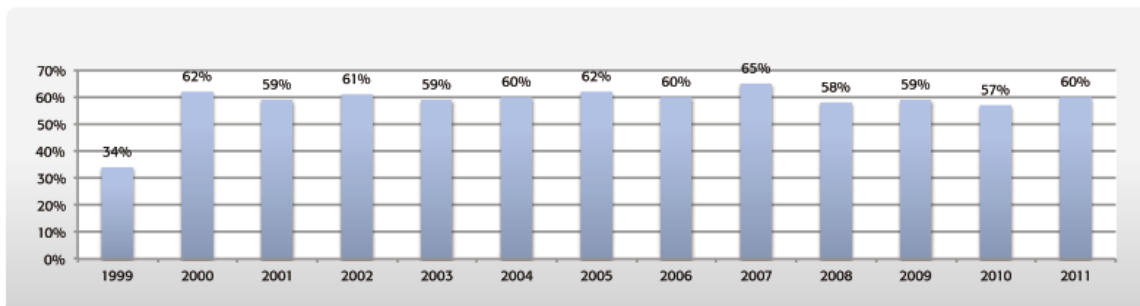
These suggestions could be varied depending on portfolio manager decision from company to one another. It means that PA could define its own strategies for setting profit margins for the system by using a proper user interface. Then bid selector agent (see Section 6.3) will be informed by receiving the appropriate message and then it can manage further decision making processes as discussed in Section 6.7.1.

6.7.6.2 KPI control rules for supply chain management

As discussed in system architecture illustrated in Figure 6.2, the KPI benchmark agent has two main roles for providing feedback to the system. The first role was discussed in the previous section. The second role is supporting decision making with respect to supply chain configuration. It means that the KPI benchmark agent works closely with the SC configurator agent (see Section 6.7.7) to support strategic decisions (i.e., supply chain configuration and partnership decisions) discussed in hierarchical integrated framework in Section 6.2.

When a project finishes, the KPI benchmark agent will be notified by PMA. Then the required information will be gathered from relevant actors based on methodology provided by (Centre for Construction Innovation, 2013) and “KPI time

Predictability” will be calculated. Afterward, this will be benchmarked with projects across the construction industry by utilising the required ontology (similar to (Lavbič et al., 2010)) and collecting data from external data sources which is KPI Engine & Zone (one of the examples is shown in Figure 6.8).



The annual KPI surveys ask for the actual out-turn time taken for the construction phase compared with the length of time agreed at the start of that phase.

Figure 6.8 Construction predictability time (Prisk, 2011)

Similar to the approach discussed in previous section, the rule models in conjunction with KPI benchmark agent for supporting supply chain configuration procedure could be set by the PA. For instance, the PA can set the rules for giving 5 extra points to those SCAs that collaboratively worked together to achieve the enterprise success, when the benchmark shows that time predictability is 5% better than the other rivals in market. This refers to reliability of the SCAs. This in turn increases the chance for SCA to become the winner in the next RFB.

In addition, it shows how effective a particular PMA can manage a project in different stages, from subcontractor evaluation in the first stage, time-cost trade-off optimization in the second stage and then controlling and monitoring the project progress in the third stage and finally handing over the project with predictability better than the other rivals resulting in more reputation for the company. Therefore, another rule that can be set by PA is promoting the PMA and assigning more important projects to him. Moreover, conducting the real case study and interviews with PAs and PMAs shed light on the idea that since sleep time in construction industry may result in staff declining, the enterprise should consider the abilities of their staff and attempt to keep them employed in sleep periods. Therefore, PA can set a business rule to promote the PMA who had a critical role in success of the project and assign them to more complex projects that need more experience and

expertise. In addition, in the worst scenario, when the enterprise is faced with sleep time, the PA should keep successful PMAs as key resources of the organisation rather than focusing on cost reduction and reducing the staff.

These rules can be set in MAS-DSS by PA through a user interface. Table 6.9 shows the suggested rules for supporting decision making in conjunction with the development of PMAs and SCAs.

Table 6.9 Time predictability KPI and Business rules set in MAS-DSS for supply chain management

Time Predictability	Suggested Rules and Decisions that can be set in MAS-DSS		
+ (0-5)%	Give 5 extra scores to the involved Subcontractors.	Give them priority for RFB if two SCAs have the same score.	Allocate projects more than £5M to PMA.
+ (5-10)%	Give 10 extra scores to the involved Subcontractors.	Conducting probability clustering procedures for key subcontractors. (see Section 6.7.7)	Encourage PMA by incentive plan.
+ (more than 10)%	Conducting probability clustering procedures for key subcontractors.	Preparing partnership agreements with involved subcontractors.	These key SCs will play the main role in bid preparation for the next projects.
- (0-5)%	Decrease 5 scores from the involved Subcontractors.	Allocate projects less than £5M to PMA.	Training courses for PMA in SC evaluation.
- (5-10)%	Decrease 10 scores from the involved Subcontractors.	Accept their bid if and only if there are not any other SCs.	Seek to find new subcontractors. Recruiting new PMAs.
- (more than 10)%	Remove those SCs who worked in the project from Supply Network.	Find new SCAs in order to reconfigure the Supply Chain.	Train the new PMAs toward collaborative working and Supply Chain Configuration.

6.7.7 Supply chain configuration

As described in 4.6.3, (configuration procedure in DIMS), after conducting project optimisation and selecting the subcontractors for each project, for the certain period of time, an agent could be empowered with a probability clustering technique, in order to detect most frequently used configuration across the previous projects as described in (Akanle & Zhang, 2008) for manufacturing systems. Although it seems that this approach is a promising method to find out the global configuration, this model needs to be modified for the construction industry.

One of the main differences between the construction industry and manufacturing systems is that manufacturing systems have a fixed location, however, construction projects are spatially scattered across geographical locations temporarily. They are usually labour consuming. Therefore, many parts of the job should be conducted by the local subcontractors because they are cheaper than others. Thus supply chain configuration and partnership agreements should be selectively focused on key subcontractors such as timber frame suppliers, mechanical and electrical (M&E) subcontractor, pods providers, door and windows manufacturers, carpet producers, furniture manufacturers etc. The other labour consuming subcontractors such as demolishers, carpenters, wall renderers etc. would be selected from local areas.

As a consequence, before conducting the procedure, the supply chain configurator agent should be able to distinguish the key resources that could serve all of the projects and identify those in the same trade that are most frequently used. This helps PA to treat the best selected key resources as strategic partners. This also informs the PMA about less used subcontractors so that they need to be eliminated from the bidding process for the next projects. It means that trust was established and the benefits and the goals of enterprise are now coupled with subcontractors' goals. However, project monitoring and periodic subcontractor evaluation still will be conducted to ensure that continuous improvement in the partnership agreement is being consolidated.

In brief, probability clustering procedure was encapsulated in the proposed model in order to cluster the subcontractors based on key and major resources (central), intermediate and local levels as suggested by Gadde & Dubois (2010). The key point in this utilization should be clustering the subcontractors based on their previous performance when subcontractor evaluation was conducted periodically and the scores of the subcontractors could be other viable criteria for clustering purposes. Since this data will need to be collected over many projects taking a long period of time, this was not tested during the current research.

6.8 Summary and discussion on adopted models

In this research the complex hierarchical multi-project planning and supply chain management has been tackled. The construction industry was investigated in order to understand its complexity, and to specify the required decision making process that can potentially improve the main contractor company performances through deploying a better enterprise management system. The in-depth case study showed that the management team required solutions to help to select projects, to evaluate and assess the subcontractors, to select the best combination of the subcontractors and different required trades of the projects, to schedule the master plans and to reschedule when required at the project level. While the planning horizons of these operational and tactical decisions are mostly short or medium term, there are some other decisions that are related at the strategic level and based on long term planning horizon such as managing the effects of commencing and finishing a project across the portfolio and finding the ways to improve the performance of the entire portfolio rather than a single project.

In the fragmented construction industry the level of variability and uncertainty is high, making the system very complex. So to the best of author's knowledge no existing research has tackled the real world problem in an integrated framework so far.

The proposed framework in the present study was constituted of several processes and procedures. In constructing the integrated framework needed to select the appropriate models for each process, relevant models were adopted from the literature and the required modifications were made. Using multi agent system architecture facilitated the integration of the adopted models which can be considered as one of the contributions of the current study. In this section a summary of the selected models and their modifications will be provided in order to highlight some of the contributions that were made in this research. Figure 6.9 shows the adapted models that were embedded in the framework.

Subcontractor evaluation is one of the main processes that has received much attention by both practitioners and academics. According to the case studies conducted in this research, it is understood that all of these companies have an in-

house developed system for quantitatively evaluating subcontractors. In the SME company (Fanavaran) the model was a simple evaluation sheet (a few general questions about the subcontractors) and in large size companies they apply more detailed multiple choice questions based on a Likert scale in which the models were not academically tested.

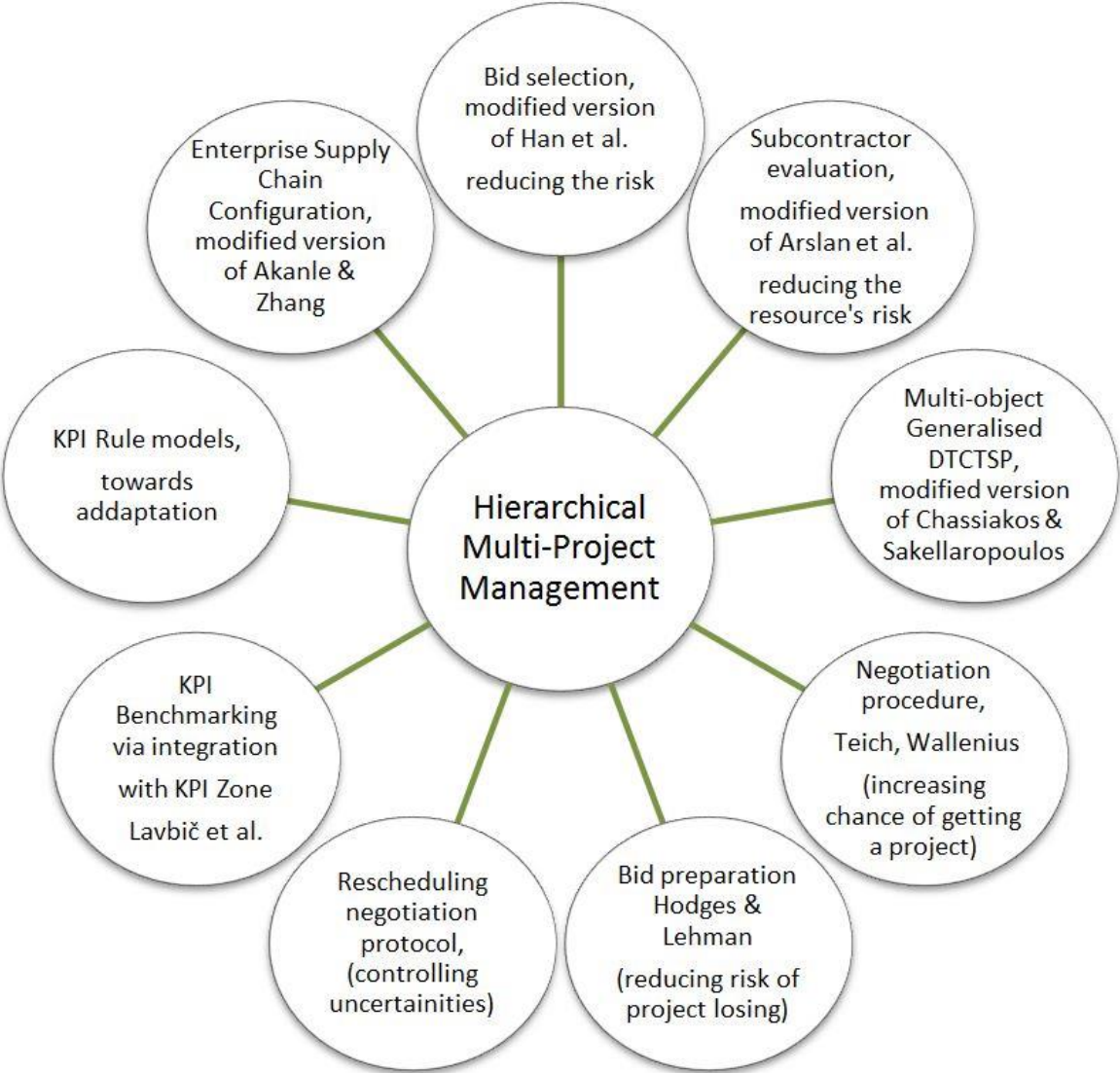


Figure 6.9 Adapted models embedded in the framework

In this research the author adopted the model that was originally proposed by Arslan et al. (2008) and applied the required modifications to make it suitable for use in the integrated framework. The original model can be used directly for subcontractor selection, however in this research it was used in the second phase of subcontractor selection (see Figure 6.4) and the final selection will be achieved

by negotiation of the time-cost trade-off solutions between the portfolio manager and the client. In addition, the feedback from the evaluation can be transferred to the subcontractors so that all the subcontractors who are willing to work with the company would be able to understand their scores. This complies with continuous improvement concepts and provides a particular subcontractor with the opportunity to improve and make itself ready for the next bidding opportunity. In brief, the modifications that were made in this study to the Arslan et al.'s model are the notion of giving feedback to the subcontractors and also combining both qualitative evaluation and quantitative optimisation (see phases 4,5,6 of Figure 6.4) for making the final decisions of subcontractor selection in a particular CFP.

In order to facilitate communication and collaboration with subcontractors, automated bidding is utilised in this research. In contrast with the other e-bidding systems such as National Procurement Service (2013) and Lenin (2011), the proposed automated bidding uses MS Outlook and transfers bids via HTML files. This makes the system more user-friendly and also eliminates the need for other data storage - the collected bids can be directly retrieved from the MAS-DSS database. Therefore the fourth phase of Figure 6.4 that deals with filtering the outliers from the collected bids can be directly carried out in main contractor companies. Moreover, the companies can keep sensitive data in their own databases rather than storing it in websites that are managed by external parties.

Project selection and bid preparation decisions are two critical tactical decisions that will be managed by project portfolio manager. This includes risk assessment of the CFP and if the project was selected, submitting the final bid to the client. Bid selection will be summarised in the following paragraphs and the negotiation procedures will be discussed later.

With respect to bid selection, as discussed in Section 6.7.1, Hans et al.'s model was adopted. In order to integrate the entire decision making framework, in this research, the ranking generated in the bid selection process is used as one of the inputs to the multi-project scheduling process. In other words, the scores that are generated by Hans et al.'s model will be used for project prioritising particularly when scarce resources are required by different work packages at the same time.

This means that if there is more than one project under the process of project selection simultaneously, the portfolio manager allocates the outcomes of the model to the CFPs that have been accepted for the bidding operations at the same time. The scores are assigned a priority weight for two aspects. First it will be used for negotiation processes which will be discussed in this section later. Second, it will be used for allocating a subcontractor to the projects. More precisely, when a project gained the lower utility rate (or higher risk level in comparison to the others) which is still higher than the minimum threshold (acceptable level), the more reliable subcontractors will be allocated to it in order to support the project manager who should manage the project. Selecting the more reliable subcontractor for a project reduces the project risk, improving the overall management of the projects and also the portfolio. Although the idea of allocating more reliable subcontractors to more risky projects was suggested by some scholars such as Artto et al. (2008) and Aloini et al. (2012), to the best of the author's knowledge there was no practical methodology that can support the concept so far. Thus the proposed mechanism in this research can link the tactical decision (bid selection for the portfolio) to operational decision (subcontractor selection for a project).

After making the bid or no bid decision (project selection), subcontractor selection (resource allocation) and master project scheduling must be addressed at the operational level. An extensive literature review and an in-depth case study were conducted in order to identify the best mathematical model that could accommodate the requirements of the proposed framework. Understanding both centralised traditional single project scheduling along with decentralised multi-project scheduling based on the notion of MAS inspired the author to adopt and modify the appropriate model and solution algorithm for multi-project scheduling along with subcontractor selection.

For adapting the appropriate models in this subsystem, beside the literature review, findings from the in-depth case study shed light upon the idea that the bidding process in the construction industry and project scheduling can be combined together based on a mathematical formulation for project scheduling called Generalised Discrete Time Cost Trade-off Problem (GDTCTP). The original

model proposed by Chassiakos & Sakellariopoulos (2005) had a single objective function in order to select different available modes for a construction project. However, in this work the model was modified to a two-objective model and a well-known genetic algorithm NSGA2 (Deb et al., 2002) was utilised as a competent solution approach. This mathematical formulation lies behind the simple user interface tools in the proposed MAS-DSS in order to simultaneously handle both resource allocation and the scheduling process. The former leads to subcontractor selection while the latter leads to providing a range of solutions for improving the negotiation with the client. Resource loading and capacity management at the project portfolio level is controlled by the blackboard system and Moderator Agent across the portfolio.

In project scheduling, the author adapts the mathematical formulation of GDTCTP that was initially developed by Chassiakos & Sakellariopoulos (2005) and proposed multi-objective functions in order to model bidding process, project master scheduling and subcontractors selection as an integrated procedure. This will be conducted in the 4th and 5th phases of the proposed approach for the integrated bidding process, subcontractor selection and project scheduling model (see Figure 6.4) which is concerned with a single project.

With respect to resource conflicts between concurrent projects, the subcontractor's capacity, load and score will be updated by the blackboard system. Then Moderator Agent manages and controls the load, capacity and risks of deployed subcontractors across the multiple projects by allocating more reliable resources to more risky projects when two project managers have conflicts for deploying a particular subcontractor in their own projects. Moreover, besides managing the resource load and capacity of subcontractors this also manages the risk of using a subcontractor who attempts to take more jobs by submitting bids to several sites' project managers simultaneously. In this way the proposed model manages the bidding processes not only at the project level but also at the enterprise level.

Thus the proposed multi-project management model is able to allocate resources and schedule concurrent projects while resource conflicts are removed by

appointing more reliable subcontractors to the more risky projects and also controlling the risk of over deploying subcontractors across the distributed projects.

This is a new approach in the construction management literature which is related to the multi-project planning and supply chain management in which it goes beyond all the research that was recently surveyed by Zhou et al. (2013).

With respect to bid preparation and negotiation process with clients which is a very important and critical phase of the entire of the system, there are two approaches that were constructed in this research. Many scholars argued that negotiation is one of the main duties of the portfolio managers (Martinsuo, 2012), however to the best of the author's knowledge there is not a particular methodology proposed by academics for improving the negotiation communication between clients and portfolio manager in the early stage of the project in the construction industry. This research addressed the negotiation process because conducting a successful negotiation at the CFP stage will increase the chance of winning the contract, it can reduce the sleep time between two sequential projects and finally it can support the sustainability of the business and its supply chain. Therefore, it is located in the heart of the model where the portfolio manager should take this tactical decision which is in conformity with Martinsuo (2012). This tactical decision can link the operational decisions of project managers for making final contracts with subcontractors and also the strategic decisions that are based on the profit margin percentage that should be added to the bid's costs. This means that when the position of the company in the market is stronger than the competitors, the profit margin can be increased and vice versa. The portfolio manager is able to identify the company position in comparison with other competitors through the benchmarking KPI rule model (Section 6.7.6) and bid selection procedures (Section 6.7.1).

This tactical decision (bid preparation and negotiation process with clients) plays a critical role at the heart of the proposed hierarchical decision making framework and dynamically links the other decision levels together i.e. operational and strategic levels. In this research, two types of bidding situations are proposed i.e.

when the CFP is negotiable and when a competitive bid submission and tendering process is required.

As it was mentioned in Section 6.7.4.1, when the bid is negotiable, the solutions obtained from time cost trade-off along with other attributes (such as guarantee periods of finishing works or maintenance period) are to be negotiated with the client in order to understand its preferences with respect to each of the attributes. In compliance with Teich et al. (2004) and Wallenius et al. (2008), MAUT is deployed to support the decision making. Thus, the collaborative decision making can be made by client and portfolio manager. The proposed algorithm in this model sorts the solutions based on the client's preferences resulting in increasing the acceptance of the bid by the client. As it will be discussed in Chapter 7, Fanavaran which is an SME that works in architectural design and EPC projects strongly acknowledged the idea. The reason was that the model can support the company's CEO who is in charge of direct negotiation with client. Since their private clients are usually seeking bespoke buildings in design and architecture, it seems that this approach is a good response to this kind of market. The idea is to design the building in different scenarios (technologies and materials), running the bidding process along with time-cost trade-off and finally offering several solutions to the client to choose. They believed that this would lead to an EPC contract rather just a design contract, which results in increasing their competitiveness in the market. It is really interesting that the perception of the management team in this company was totally in line with the framework that proposed by Hans et al. (2007). Although in Hans et al.'s framework three distinct functional planning areas i.e. technological planning, resource planning and material coordination (see Figure 2.1) was advised, little attention was devoted to the technological planning domain. However, according to the findings from the case study in this research, the proposed model provides a valid approach to integrating and exchanging the information across all three abovementioned domains.

It is worth noting that the other case study companies that work in large scale construction projects and do not have a design department were interested in the second approach i.e. the competitive bidding procedure proposed in Section 6.7.4.2. In these cases the design phase is usually carried out by other

companies and the drawings are ready in tender package, and therefore the portfolio manager needs to submit the company's bid to the client in a sealed envelope. In this case, the uncertainty in the decision making is recognised as ambiguity (Zavadskas et al., 2008). In this decision making condition, the portfolio manager does not know the preferences of the client and also he/she does not know which other competitors have taken part in the client's tender process. In this case he/she should select one of the solutions from time-cost trade-off procedures (or any other scenarios that he/she has obtained by other ad hoc approaches) and after adding up other charges such as tax, contingency cost, profit margin, etc., he/she should submit the bid to the client. In this case, the portfolio manager should rely on his/her previous experiences (and might rely on the knowledge that was gradually gained in the MAS-DSS database). Thus, according to the innovative approach that was proposed in this research, Hodges & Lehmann's theory (1952) was adopted as an application of this theory which can support portfolio manager for making decision based on previous experiences and knowledge. The model supports the portfolio managers to control their risk level which stems from lack of knowledge of the client preferences and of the company's position in comparison with other opponents in the tendering process. The idea was strongly acknowledged by large scale companies who are involved with submitting bids to the clients. It was obvious that they had been involved with similar conditions many times and they were striving for a solution for this decision making process which is full of ambiguity.

With respect to rescheduling issues and managing uncertainties that may affect the project baseline schedule, based on findings from the conducted in-depth case study, it was understood that the interdependency between construction projects is low and the variability of the projects is high which is in compliance with Herroelen & Leus (2004a) and Hans et al. (2007). Therefore, to manage project scheduling and rescheduling in the proposed model, the project is considered to be scheduled in advance, establishing a baseline schedule which could be a part of a contract. Then reactive scheduling needs to be carried out when an unexpected event happens. Thus in this study, a rescheduling negotiation protocol was proposed as a new contribution in order to manage the uncertainty that might be caused by a

subcontractor and might be needed for rescheduling the project. The developed rescheduling negotiation protocol was empirically validated by several project managers as well as a lawyer who was expert in the construction industry.

Finally, “when a project is finished, the lessons learned are linked to whether the project was delivered on time within cost and to the agreed quality” (Atkinson et al., 2006). The proposed framework aimed to take advantage of lessons learned from the past experiences across the distributed projects and different project managers who may stay or leave the company. The devised MAS-DSS planned to address the KPI indicators and use them as a system adaptation mechanism for future projects. The KPI Engine & Zone was adopted as the most commonly used approach in the UK construction industry. The other option for adopting KPI benchmarking was the framework that was proposed by Bassioni et al. (2005). However, as they suggested in their further research works section, this framework needs to be studied deeper in order to be generalised for two aspects, for using it in international projects, as well as using it in SMEs. Thus, an agent called Benchmarker is introduced in order to facilitate the data transmission to and from the external data source (KPI Engine & Zone).

Moreover, similar to the research conducted by Lavbič et al. (2010) and Piramuthu (2005) in other domains, two rule models were constructed to align supply chain configuration of the enterprise (the strategic decision which is related to partnership agreement decisions) and bid selection (tactical decision) with subcontractor selection and allocation and project scheduling at the project level that should be made by project managers at the operational level.

The supply chain configurator agent is the other module that is embedded in the proposed framework which can be considered as a new solution beyond the study conducted by Eom et al. (2008) and also as a practical approach towards partnership agreement as it was called for by Artto et al. (2008). It detects the most reliable and sustainable subcontractors and puts them into clusters. In the present research, the probability clustering algorithm was adopted for clustering the best performance subcontractors in construction industry in different groups such as best practices in a particular trade, geographical clusters, or local, intermediate and central as suggested by Gadde & Dubois (2010). This could lead to partnership

agreements with the most resilient subcontractors who could do high quality projects in limited time windows. All of the case study companies acknowledged the usefulness of this module and strongly sought to use it as soon as possible.

The successful management of these interrelated decisions is expected to increase the enterprise's reputation and also trust between different involved actors across the supply chain. Ultimately, these should lead to expanding the main contractor market share and reducing sleep time between projects. These can also lead to configuring the supply chain across the portfolio rather than solely each individual project which can lead to partnership agreement in long terms.

6.9 Summary

In this chapter, the integrated framework in the form of an MAS-DSS was proposed. It includes complex rules, each of which will be used by agents including CAs, PA, PMAs, and SCAs. These rules will be run whenever required by agents to facilitate decision making and resolve the problems when they interact, communicate or negotiate with each other in different levels of the hierarchical project portfolio planning. Multi agent architecture allowed the author to design a DSS system to link these interdependent decisions in an integrated framework that can be spatially distributed across different locations.

Although subcontractor selection and project/bid risk evaluation have been addressed by other researchers, in this research I integrated them with other decision makings rules including subcontractor selection, project scheduling, bid preparation and supply chain configuration. I showed how these decisions have effects on each other and determined the links between them. The feedback and control system plays the critical role in these rules where these decisions will be affected by the KPI's and benchmarked competitors when risk management in competitive construction market is highly important.

The supply chain configurator that was introduced in the construction industry by this research work could be a proper solution that allows learning from the past to be used to form the supply chain network. This implies a novel method in the

construction industry that is based on manufacturing systems design (Pakgohar & Zhang, 2012).

In the next chapter, first the prototype MAS-DSS system will be demonstrated and then explained how it utilised to validate and evaluate the proposed model and framework by the practitioners.

CHAPTER 7 EVALUATION OF THE PROPOSED FRAMEWORK

7.1 Introduction

In chapter 6 the proposed integrated framework for managing the complex project portfolio and supply chain operations in construction industry was illustrated. As it was mentioned, the model was constructed based on reviewing the literature and conducting an in-depth case study of the ongoing student accommodation project at the University of Exeter. This framework consists of several procedures to integrate the decision making in three decision making levels i.e., operational, tactical and strategic. So, this framework could be utilised for developing a commercial enterprise total solution for construction companies. This chapter is devoted to evaluation of the proposed framework.

For this purpose, first a prototype MAS-DSS enterprise system has been developed that partially accommodated the designed features and procedures of the framework. This facilitated the evaluation process by practitioners. Second, the MAS-DSS solution was presented to a group of practitioners in the case study company (UPP-ltd). The evaluation carried on based on an open-ended interview with four practitioners and causes insightful feedback which led to a significant revision on the framework. Therefore, the feedback from the first group of practitioners was taken into account and the model revised in order to accommodate the features that discussed in the first empirical validation process. Third, several other case studies have been planned in order to capture the opinions and notions of practitioners who were not involved with the developing process in order to evaluate and validate the proposed model externally. The case studies were selected from different range of construction companies from national and international perspective. By the help of the MAS-DSS, practitioners were able to visually see the model's features and compare them with their existing enterprise models.

In this chapter, first an overview of the proposed software solution will be demonstrated. Then some snapshots of the developed MAS-DSS system will be presented. After introducing the MAS-DSS, the evaluation process will be described in detail.

It is worth noting that for verification of the mathematical models and optimisation parts of the framework the numerical examples were described in Sections 6.7.3.1 and 6.7.4.

7.2 Overview of the MAS-DSS Solution

The multi-project management problem has three types of parties, the clients, the main contractor management team including the portfolio manager and the project managers, and all the subcontractors. Their relationships have been identified in terms of the activities that link them. Thus the client selects the main contractor based on trust, performance and reputation. The main contractor identifies appropriate subcontractors based on qualitative evaluation, their performance and their bids through the automated bidding process. The subcontractors' bids are formed into alternative project schedules which satisfy the client in different ways and can be selected by the time-cost trade-off. This novel framework conceptualises the problem in an original way that allows the project management activities to be operated using a DSS with additional communication which facilitates collaboration between these parties.

A schematic demonstration of the integrated MAS-DSS is shown in Figure 7.1 and a review of the system is presented in this section.

The MAS-DSS model consists of the four layers. At the internal layer i.e. the core of the model, a blackboard system handles all of the required information that exists in the distributed projects across the enterprise.

The Communication layer facilitates interoperability and communication between main actors. CFPs and clients feedback will be transferred between clients and the portfolio manager while RFBs and subcontractor scores are transferred between project managers and subcontractors.

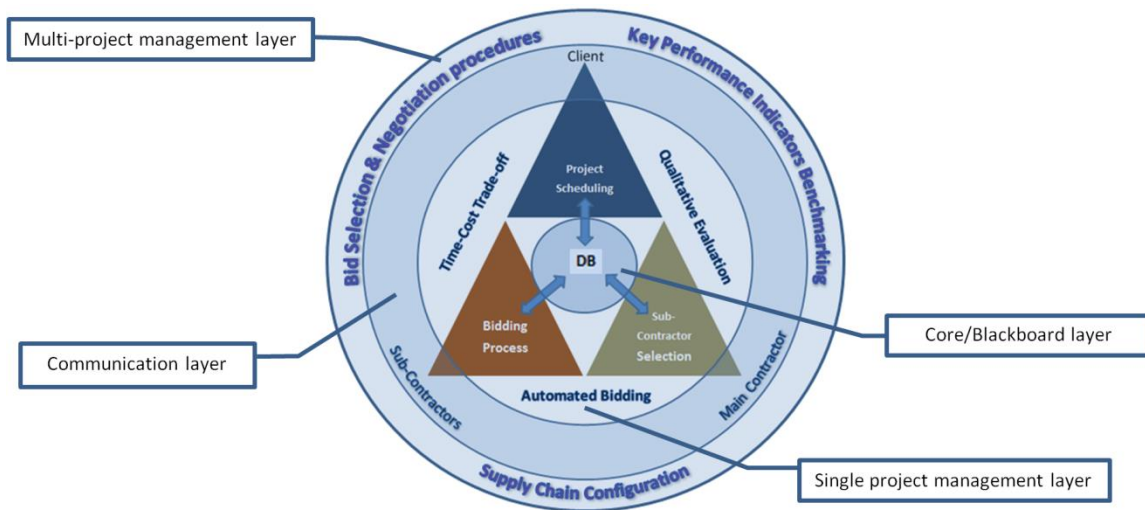


Figure 7.1 Integrated MAS-DSS models for construction multi-project management

In the single project management layer, the automated bidding process, quantitative evaluation of subcontractors and project scheduling model (based on time-cost trade-off procedure) are handled. These processes can be conducted for each project to achieve the best combination of the subcontractors for the project level. This is configuring the supply chain of each project for a particular client. This layer is dealing with each individual project that is managed by an autonomous project manager. Each of the project managers has access to the system, and can retrieve the project information to make their own decisions. The decisions are made based on the communication between subcontractors and the collected bids in response to RFBs for each project. The communication between subcontractors and project managers will be handled by the automated bidding process. Prior to this process, a qualitative evaluation should be made by project managers in order to select the eligible subcontractors for sending the RFB to them. Project managers are also able to control the project progress and reschedule the project. Project managers can share information on the eligibility of subcontractors and their scores with each other across the enterprise supply chain. This will support the organisational learning and using the lessons learned by them.

In the outer layer, bid selection and negotiation procedures, Key Performance Indicators Benchmarking and the enterprise Supply Chain Configuration will be handled by the portfolio and enterprise management team. The portfolio manager monitors and controls the entire system through effective communication with

clients and the appointed project managers who are responsible for handling particular CFPs and its related projects. The project managers are also appointed to the projects based on their competences and their previous performance (see Section 6.7.6.2 and Table 6.9).

Thus, the proposed framework can address the decision making requirements both at the project level which should be made by project managers as well as at the portfolio level in which the decisions should be made by the portfolio manager. In addition, uncertainties that are unavoidable parts of the decision making in the construction industry are managed by the use of appropriate procedures at these two managerial levels.

Since the model is based on the feedback mechanism, adaptation will be achieved by continuous improvement that aims to dynamically manage the complexity of the multiple projects environment. The complex decisions including bid/no-bid decisions (project selection), project scheduling and subcontractor selection, tender preparation and negotiation with clients and also supply chain configuration are interdependent decisions that will be supported by the proposed integrated MAS-DSS framework.

While project managers are responsible for their project autonomously, overall performance is monitored and controlled by the portfolio manager at the tactical and strategic level. The global optimisation across the enterprise will be attained by improving the communication, coordination and negotiation between clients, portfolio manager, project managers and subcontractors. This will be achieved by KPI benchmarking and making the strategic decisions to manage, adjust and control the entire portfolio. The improvements at the operational level as well as overall improvements across the enterprise will be evaluated and monitored periodically.

Since the highly fragmented construction industry suffers from sleep time between two subsequent contracts (Arto et al., 2008), the better coordination between the agents involved in the portfolio can support inter-organisational collaboration and ultimately reduce the sleep time. Through this collaboration, the chance of winning a potential CFP will be increased which in turn can lead to reducing the sleep time

for the enterprise. Consequently, this will lead to partnership agreements between construction companies and its supply chain and towards the better collaborative working as discussed by Xue et al. (2010).

A significant step forward in the study is that the framework dynamically integrates three levels of decision making in a single MAS-DSS platform as discussed in Chapter 6. In the next section some of the features of the system are presented.

7.3 Some snapshots of the developed MAS-DSS

The software was designed in the Microsoft Access 2007 environment and captured the benefits of integration with other Microsoft Office packages including Excel and Outlook.

The proposed model and its corresponding DSS software were developed gradually by conducting a case study in UPP. In the software, portfolios can be defined along with their corresponding projects. In Figure 7.2, the general specifications of the portfolio in operation at the time of the study at the University of Exeter are depicted.

The screenshot shows a software interface titled 'Portfolios' with a blue header and a building icon. The main area contains several data entry fields:

- Portfolio Name:** University of Exeter
- Portfolio Manager:** Ron Allen
- Contact Tel No:** 01392723613
- Email Address:** info@upp-ltd.co.uk
- University:** (Section header)
- University Manager:** Nikola Baker
- General Contractor:** Balfour Beatty
- Manager:** Nick Wilkie
- Contact Tel:** 01392273641
- Contact Tel:** 07919345282
- Email Address:** info@exeter.ac.uk
- Email Address:** info@cowlin.co.uk
- Start Date:** 1/7/2009
- Finish Date:** 15/9/2012

On the right side, there is a 'Note' box containing the following text: "Constructing student accommodations in different locations of campus. A £133 million initiative to increase the amount of on-campus student accommodation. The initiative is a vital part of the University's £450 million investment programme."

At the bottom, there are five buttons: 'Portfolio Details', 'Project Details', 'Traders Database', 'Portfolio Optimization Toolkit', and 'Bid's Estimator'.

Figure 7.2 Defining portfolios

Figure 7.3 presents one of the projects making up the university portfolio, a 6-storey block of 4550 square metres including 190 en-suite student rooms located at Lafrowda, the west corner of the University of Exeter campus. The work

breakdown of the project based on the required traders is accessed through a tab from this screen.

Figure 7.3 Defining projects and their work packages.

Figure 7.4 demonstrates how the traders, subcontractors and manufacturers can be defined in the database. The scoring sub-system based on the methodology proposed by Arslan et al. (2008) (see Section 6.7.2) is utilized to assign an appropriate rank to each trader based on its performance in past project.

Figure 7.4 Defining trades and scoring them

This step (see stage 2 of Figure 6.4) of the selection process is qualitative and the project manager's behaviour plays a crucial role for the rest of the process. This is a measure of the GC's preference for the particular subcontractor. The traders are sorted based on their scores and the project manager can select those with higher rank as shown in Figure 7.5.

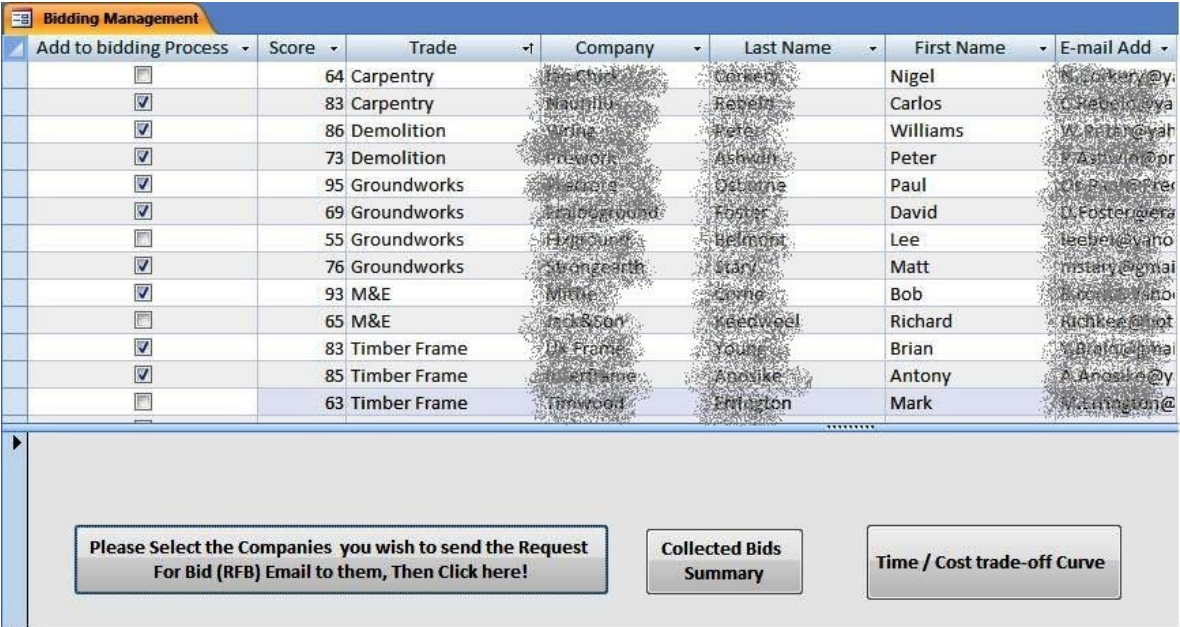


Figure 7.5 Selecting the SCs based in their score and sending RFB electronically

It is an interactive dialog box which allows project manager to select/deselect the traders based on their rank, the number of available traders for each work package and the number of projects that the GC is currently involved with. These parameters are controlled by Moderator Agent (MA) who has access to blackboard and knows the available capacity and total loaded of the subcontractors across the portfolio.

According to Stage 3 of the integrated proposed model (see Figure 6.4), the tender package will be transferred electronically to the SCs selected in the first step. The software and the database were easily linked to Microsoft Outlook for the purpose of the data transfer to the subcontractors, i.e. to send and receive the bids via HTML pages which transfer data from the project manager's Outlook to the subcontractor's email accounts. Traders have to reply to the RFB within a pre-determined deadline (tendering period) (See Figure 7.6). The bids will be received by the email system and the bids database will be updated automatically.

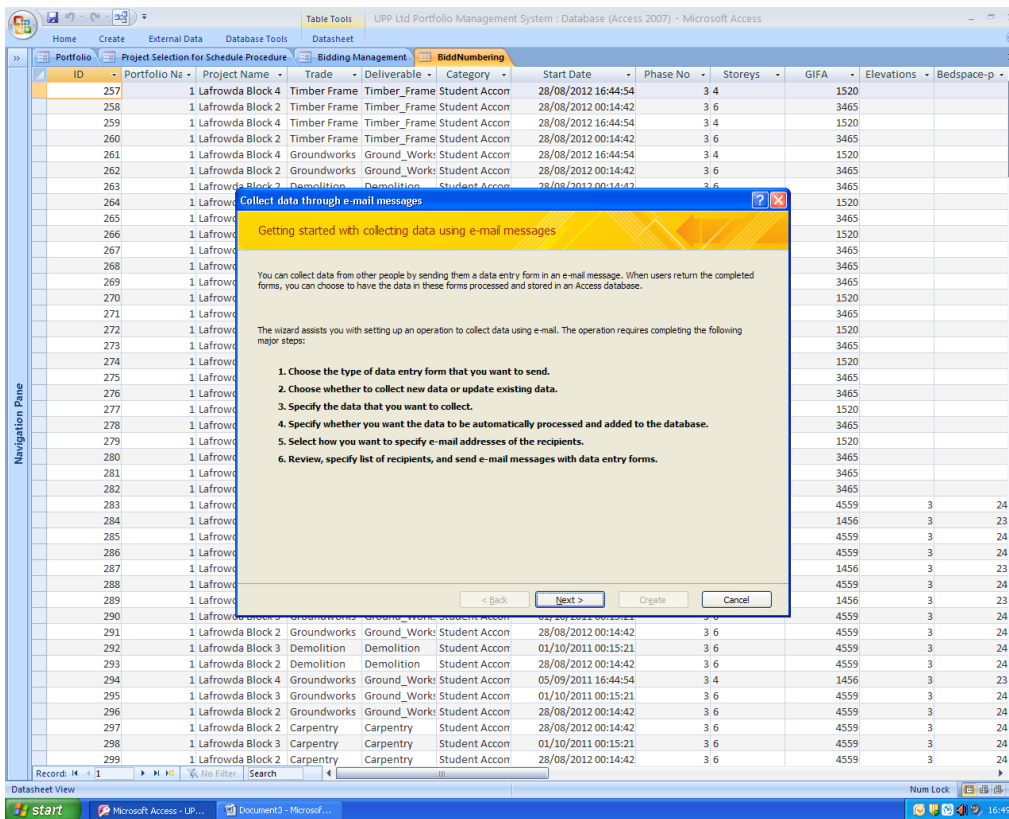


Figure 7.6 Automated bidding process

The next step of the interactive MAS-DSS solution is assessing to find the outlier bids by considering a predetermined percentage from the average price bids. Further to this stage, a time-cost trade-off scheduling problem will be formulated and solved (Stage 5, Figure 6.4). For this purpose, PMA utilises an external optimiser. The automated link between Access and Excel allowed PMA to use SolveXL (Savić et al., 2011) as an optimisation unit in the MAS-DSS for covering the optimisation process.

According to North & Charles (2007), using external software in multi agent systems increase their performances due to the fact that external optimiser has been tested and verified in terms of computational speed and accuracy. Thus, this approach has been widely accepted among different multi agent system software engineering methodologies such as JADE (Nikraz et al., 2006). Therefore, in this MAS-DSS, SolveXL (Savić et al., 2011) and particularly its procedures on NSGA2 has been adopted as an external optimiser agent with excel user interface. This provided a suitable platform for real world practitioners (i.e. physical project

managers) to interactively work out MS Excel user interface to find out the time-cost trade-off solutions.

Using the collected data discussed in Chapter 5 and particularly depicted on Table 5.2, and based on the activity precedence constraints which represent the sequence of the work packages, the time-cost trade-off optimisation was formulated in Excel which was then solved by SolveXL. Due to the requirements of confidentiality in the building projects which prevent showing the detailed information, in this section, Figure 7.7, just provides an illustration of the Pareto-front curve, as provided by SolveXL. However, in Sections 4.8 and 6.7.3.1, comprehensive examples from test cases were provided.

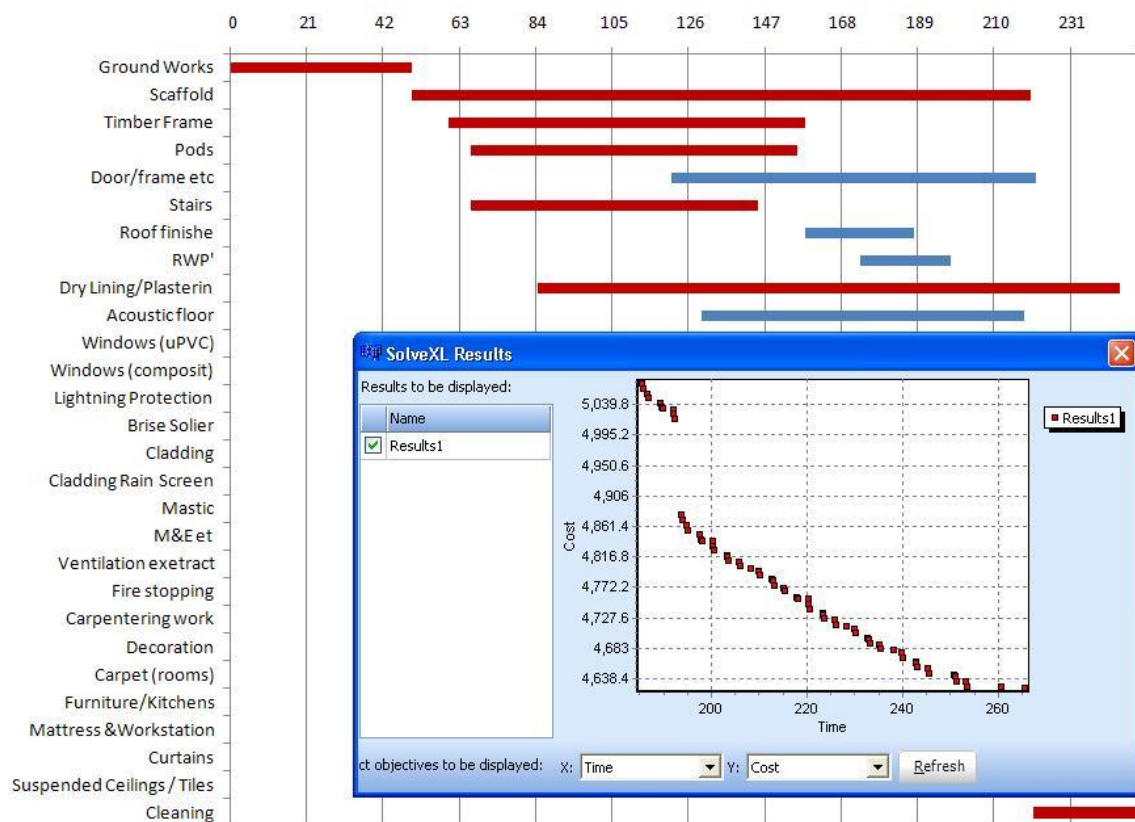


Figure 7.7 One of the solutions from the Pareto-front Curve and its corresponding Gantt Chart

Each point on the chart represents an alternative project solution, ranging from more expensive, shorter durations at the top left to longer duration cheaper solutions at bottom right. The user can click on any particular solution in the curve to come up with project schedule and its corresponding subcontractors.

The results was compared with the actual project contract and showed that the contract was set based on one of the obtained solutions, providing confidence verification of quantitative part of the integrated solution.

7.4 Empirical evaluation of the proposed decision making framework

Since this study aimed at addressing real world problems and providing a solution for managing the complex project portfolios in construction industry, as mentioned in chapters 2 and 5, acquiring feedback from practitioners deemed a vital part of the study.

The proposed framework as a total solution has been presented and investigated in four construction companies in order to be validated. This has been conducted to ensure rigour in the research outcomes as internal and external validation by practitioners. Complexity, plausibility, practicality and usefulness of the system were questioned and interested companies were invited to implement the system.

In this section first the empirical evaluation that was conducted by the in-depth case study company will be explained. Then, the received feedback from other case study companies will be elaborated.

7.4.1 Internal evaluation

In order to validate the proposed framework for construction enterprise decision support system, a formal interview was planned on 15/09/12. First, the software and the results were presented to the University of Exeter contract manager and the management team of the UPP in Harrison Building, University of Exeter.

Table 7.1 indicates the position of the delegates in the meeting.

Table 7.1 Experts who attended in the presentation meeting

From	Position
Upp ltd Headquarter	Group Construction Director
Upp ltd University of Exeter and University of Reading	Construction Project Manager
Upp ltd University of Nottingham	Construction Implementation Manager
University of Exeter	Contracts Accommodation Manager, Client Representative
University of Exeter	Research Supervisor

The presentation was followed by an open-ended interview to capture their opinions on plausibility, usefulness and practicality of the system. In addition, particular questions were asked in the meeting in order to understand how they usually deal with uncertainty and project rescheduling where the replacement of a subcontractor would be essential and how they substitute a new trader in these occasions. The questions focused on the following themes.

- 1- In the current project, how many of the subcontractors do work properly and on time?
- 2- How often do you decide to change one subcontractor in an ongoing project of the portfolio?
- 3- How many of the subcontractors are replaced by you from the project because of bad working?
- 4- How long does it take to replace and allocate a subcontractor?
- 5- What were the effects of these replacements on the project schedule?

The interview was recorded and transcribed in order to analyse the practitioners' viewpoints.

In brief, four experienced managers were able to evaluate the proposed model and its corresponding MAS-DSS solution. They found that the ability to select project options and have the complete schedule produced was a significant step forward from their current practice and it would support the negotiation process with their clients. In particular, they commented on the advantage of being able to know the cost implications and possibilities for accelerating a project. Their evaluation of its practicality and usefulness raised some fascinating feedback such as "of course, it's like pulling it all together. It is a holistic approach." or when the other project manager said: "This makes my job easier." or when the UPP Group Construction Director said: "I have found that extremely interesting , ... what you have done was absolutely fantastic, the time you have taken to put that together". Finally the Contracts Accommodation Manager said: ... "So, I am really pleased and they were obviously very impressed as well which is so good".

In addition, based on their notion on dealing with uncertainty, the revision of the framework was triggered. Further to the analyses of the interviews, it was understood that there is a big gap on perception of risk assessment between academic (professor Zhang, my supervisor's view point) which mostly focused on

Probability-Impact approach and practitioners approaches which emphasised on subjective evaluations. Thus a literature review on uncertainty and risk analysis was planned to identify the more appropriate methods proposed by scholars for closing this gap and taking into account practitioner's requirements. This led to the development of the second version of the integrated model which encapsulates bid risk assessment, and also proposes a new solution for improving the negotiation between clients and General contractors where decision should be made under ambiguity as well as developing a protocol for rescheduling as discussed in Sections 6.7.1, 6.7.4 and 6.7.5 respectively. It is worth noting that the latter part was investigated by the help of another interview that was planned with a lawyer (Mr Jim Gorrod from FootAnstey). The interview was conducted following his talk in "Construction Law Update" a particular seminar held by Chartered Institute of Building (CIOB) to understand how this approach is complied with the new changes in construction law. This interview was conducted on 21/10/13 as one of the empirical validation stages. The interview was recorded and is available in the case study library as well. The strong positive response was received which explicitly supports the method.

7.4.2 External evaluation

In previous section, the process of validating the proposed model by the practitioners who were involved with development of the model was discussed. They were dealing with the processes such as project risk assessment, subcontractor assessment, project scheduling and control, and supply chain enhancement in construction industry for at least 25 years. They found the proposed model very useful and practical for their decision making processes.

The above mentioned evaluation was conducted by the practitioners who participated for developing the framework. However, in accordance with the research methodology discussed in chapters 1 and 5, four other case studies and interviews were conducted as external validation.

To do so, first a validation sheet was designed to facilitate validation process and help practitioners to evaluate the entire proposed framework in a systematic manner. This approach is a commonly used methodology when the practitioner's

perception should be captured and used by several researchers such as (Weaver, 1995), (Bassioni et al., 2005), (Taroun & Yang, 2013) .

The subsystems of the proposed framework were grouped into four main categories as follows:

- 1- Subcontractor Management: Subcontractor Evaluation, Bidding process and communication, Subcontractor Selection and ultimately Supply Chain configuration
- 2- Scheduling / Time-cost trade-off: Planning and Scheduling, Time-cost trade-off, Rescheduling negotiation protocol
- 3- Project/bid selection and bid preparation decisions: Risk assessment of the bids, Negotiable projects, competitive bidding process
- 4- KPI Rule models: Integrated KPI management with KPI Engine and Zone, KPI control rules for project/bid selection, KPI control rules for Supply Chain Configuration.

Apart from the above mentioned categories, the participants were asked to evaluate the comprehensiveness of the integrated framework and also to compare it with their current practises in the organisation.

For each group, participants were asked to evaluate four criteria in 1 to 10 Likert scale including Simplicity and Practicality, Clarity of methodology, Time and resource consumption, Quality and Usefulness of the results as shown in Appendix D. The criteria were selected in conformity with the literature in similar research fields (Taroun & Yang, 2013).

Using the designed validation sheet and the MAS-DSS prototype presentation, four organisations aimed to be considered in external evaluation phase as discussed in Chapter 5. The details of each evaluation will be discussed in the following subsections.

7.4.2.1 Estate Development of the University of Exeter

The first empirical evaluation that will be discussed is still in the context of the University of Exeter construction projects. It is based on an interview meeting with the Director of Estate Development of the University on 10/12/13. He has over 30

years' work experience which was started as an Architectural designer and then gradually moved to managerial aspects of construction industry. He is responsible for selecting the contractors, contracting and managing all of the construction development projects across the University of Exeter. After a precise investigation and detailed discussion, he evaluated the framework based on 1 to 10 Likert scale as presented in Table 7.2.

Table 7.2 the proposed model evaluated by Director of Estate Development of the University of Exeter

Criteria for system evaluation	Simplicity and Practicality	Clarity of methodology	Time and resource consumption	Quality and Usefulness of the results
1- Subcontractor Management	8	8	7	9
2- Scheduling / Time-cost trade-off	8	8	8	9
3- Project selection and bid preparation decisions	8	8	7	8
4- KPI Rule models	8	8	7	7
Comprehensiveness of the Integrated system	8	8	7	8
Compare with existing approaches	null	null	null	null

During the presentation of the proposed framework, he examined the model through scrutinising questions. The interview was recorded and exists in the research database. He focused on the strengths and weaknesses of the current practises in hierarchical project portfolio management in construction industry. One of the main issues discussed in this interview and led to his evaluation, was investigation of Figure 6.3 where the complex dynamic construction project portfolio system is proposed. He acknowledged thoroughly the plausibility of the complex model. It is worth noting that, the initial academic perception of the bid fluctuation cost, with respect to the increasing or decreasing of the subcontractor reputation and experience (as discussed in Section 6.6.1), could lead to an economic equilibrium point in bidding model. However, he mentioned that he never remembered this equilibrium condition during his 30-year experience in this market and working with many subcontractors and clients. Other complex factors such as economic condition in stock market, changes in bank interest rates and so on are also major factors making subcontractors to stay in or leave the market.

Furthermore, he emphasised the fragmented supply chain in construction industry and supported the idea of supply chain configuration based on their performances in the past projects and lessons that were learned which embedded in the proposed model. Additionally, he put emphasis on the idea of the knowledge management when the skills and expertise of the companies could be easily lost when a particular expert leaves the enterprise. In line with this, he acknowledged the proposed integrated database that maintains and shares the records of performances of subcontractors and also project managers. Project managers experiences who are dealing with selecting and working with subcontractors is valuable knowledge, it needs to be maintained within the enterprise. To do so, the decentralised MAS-DSS that uses a shared blackboard/ database, can maintain that knowledge and share it across the portfolio and several autonomous project managers. Therefore, even if they want to leave the company after a number of years of working, their knowledge, at least to some extent, could remain in the system.

Furthermore, he evaluated the system from the perspective of a major construction client in South West of the country; therefore, he was not able to evaluate the last question in the evaluation sheet. However, according to the score he gave, it seems that the proposed tools and particularly the integrated time-cost trade-off, subcontractor selection and negotiation procedures would be viable tools for general contractor companies who are interested to use the new methods and improve their negotiation competency in the current tight market.

Both the internal and external evaluation processes discussed so far, were concentrated on university-based construction projects. Particularly, UPP management team and the University State Development Manager have worked for many years in a special type of market which is university construction development. In university-based construction market, often clients are more intelligent than the other sectors because of the nature of the market which is university. They are dealing with academics and well educated people. Thus, making contracts in this market seems to be more challenging than the other sectors. It means that contractors need to adopt more powerful tools for enhancing

negotiability and also appointing subcontractors with higher quality in order to convince the universities to make contracts.

The above argument stimulates the author to externally evaluate the proposed framework in other market's segments including international companies. Thus, as discussed in chapter 5, three other companies that are active in construction industry with different sizes and backgrounds were chosen to investigate the validity, efficiency and also applicability of the proposed framework in other construction sectors. In the next subsections the evaluation process that conducted by Kayson Inc., Interserve plc. and Fanavaran Co. will be explained.

7.4.2.2 Kayson's Management team

As it was mentioned in chapter 5, during two separate meetings and getting engaged with practitioners from Research & Development Department and also the Tendering Department in Kayson, the evaluation process was conducted. The expertise and position of the practitioners who evaluated the system are listed in Table 7.3.

Table 7.3 List of Experts interviewed in Kayson Inc.

Position	Education	Years of Experience
Research & Development Department Manager	MSc Civil Engineering	32
R&D Deputy Manager	MSc, EMBA	16
Senior Quality Assurance Engineer	BSc Industrial Engineering	9
Tendering Manager	MSc Civil Engineering	18

In total over 12 working hours were spent to investigate the adopted processes within the framework and its counterpart MAS-DSS tools. The integration of the processes was also critically analysed.

In this subsection, the results of the evaluation are reported based on their perception of practicality and usefulness of the model. Since Kayson is a large size company, they set two separate meetings to evaluate the model by experts who work in the relevant departments. It means that some parts of the framework which were more related to system performance management were evaluated by the Research & Development Department while some parts of the framework which was more related to agent coordination, communications, and tendering and

relationship between clients, subcontractors and company where investigated by the Tendering Department.

Mr Golam Reza Hemmatee the Research & Development Department Manager who has over 32 years' working experience in industry and has been working in Kayson company since the very beginning of its establishment, claimed that many academic models are not relevant to the industry, because often the scholars are not involved with real world problems. Nevertheless, he supported the study and after careful evaluation of the proposed methodology in his department, he put forward the idea to Tendering Department. In the Tendering Department the management team found the proposed model useful and applicable in particularly building projects. However, they were cautious to admit time-cost trade-off and negotiation procedures for infrastructure projects. They believed that in large scale public infrastructure projects, they should usually bid for minimum price. Moreover, total makespan of the projects is not often negotiable and they had to force their subcontractors to accept their work packages based on their dictated time windows. Therefore, they welcomed the model and are willing to implement the proposed model in the Building and Housing division. In addition, apart from time-cost trade-off optimisation which they believed is not suitable for infrastructure as well as Oil and Gas projects, they were interested in exploring other features of the model as a pilot study in one or two of their active sites. For instance, although they had established an in house mechanism for subcontractor evaluation, they acknowledged the comprehensiveness of the adopted model in this subsystem and the proposed mechanism for using this assessment model as the basis of supply chain configuration. More precisely, they were interested in the proposed mechanism for supply chain configuration based on KPI benchmarking and evaluation of the subcontractors at the end of each project where system adaptation will be occurred in response to dynamic changes in market environment. The average scores obtained from these departments as the main owners of the system are presented in Table 7.4.

Table 7.4 The proposed model evaluated by Kayson Inc.

Criteria for system evaluation	Simplicity and Practicality	Clarity of methodology	Time and resource consumption	Quality and Usefulness of the results
1- Subcontractor Management	7	7.5	7.5	7.5
2- Scheduling / Time-cost trade-off	8	6.5	7	6.5
3- Project selection and bid preparation decisions	8.5	8	8	8.5
4- KPI Rule models	7.5	7	6	7
Comprehensiveness of the Integrated system	8	8	7.5	7.5
Compare with existing approaches	7	7	7.5	9

As scores show, the average evaluation of the proposed model by these two departments adheres to this conclusion that in general, Kayson acknowledges the usefulness and practicality of the system while some modifications need to be applied prior to implementing the system in this company. It was suggested and agreed that a research action should be conducted in Building and Housing division in order to tune the system parameters and rules. In the second step, the framework can be modified/ revised in order to make it suitable for infrastructure projects and Oil & Gas projects as well.

In brief, research collaboration for implementation was agreed which is out of the scope of this research project.

7.4.2.3 Interserve's Management team

Although it is understandable that usually in large scale companies for dealing with evaluation of enterprise solutions, processes and tools, the headquarters would be involved, in this case study, the author took the advantages of interview with local practitioners of Interserve plc. in Exeter Regional Office. There were two reasons for this. Firstly, it was because of cost and time limitations that restricted the interview with the headquarters' management team. Secondly, it was an opportunity for implicitly assessing and identifying whether the system might be suitable for the companies in small cities like Exeter or not.

The practitioners who are listed in Table 7.5 evaluated the proposed model in a meeting which lasted approximately 2 hours.

Table 7.5 List of experts interviewed in Interserve Inc.

Position	Education	Years of Experience
Managing Estimator/ Head of Regional Office in Exeter	N/A	23
Business Improvement Manager	BA Business	11
Project Manager	N/A	29

Since the Interserve’s Exeter Regional Office is a small office dealing with local projects, their evaluations were based on their perceptions of the system and their current requirements. The average scores for each criterion are shown in Table 7.6.

Table 7.6 The proposed model evaluated by Interserve Regional Office in Exeter

Criteria for system evaluation	Simplicity and Practicality	Clarity of methodology	Time and resource consumption	Quality and Usefulness of the results
1- Subcontractor Management	4.7	6	5.7	5.7
2- Scheduling / Time-cost trade-off	4.3	6.7	7	5.3
3- Project selection and bid preparation decisions	6.7	7	6.7	7
4- KPI Rule models	6.7	7	6.7	7.3
Comprehensiveness of the Integrated system	6.3	7	6.3	7
Compare with existing approaches	5.3	6.3	6.3	6

The practitioners kindly shared their information about the business environment in this regional market. They believed that the amount of building or refurbishment project in this part of the country is not enough to encourage subcontractors to compete each other. They usually struggle to find the right subcontractor that would be willing to carry out a particular work package in a specified time window in this regional market. They sometimes need to correspond with a particular qualified subcontractor several times in order to chase the RFB. Therefore, they hardly could collect several bids for a particular work package of a project. Because of these circumstances, they believed that subcontractor selection based on a time-cost trade-off procedure does not seem to be relevant to their regional market. Trevor Bond, the head of office commented “The presentation was very interesting and obviously you have put a lot of effort and thought into the ‘process-mapping’ etc, however, I would have thought it is probably more suited to the way

'Major Projects' rather than Regional Building. Therefore, the scores reflect our perception from the point of view of 'Regional Building', however, scores would most likely be higher from 'Major Projects' ...".

According to his comment, it seems that the implementation of the entire framework especially time-cost trade-off and negotiation mechanisms with clients are not practical for small projects located in small cities, because there are not too many qualified subcontractors in local markets. Furthermore, with respect to subcontractor evaluation and also the bid selection procedure, there are two different in-house developed spreadsheet procedures which are used across the Interserve Offices around the world. They kindly shared these models with the researcher. The author analytically compared these methods with other two adopted models in the framework in order to highlight their benefits. It was revealed that these procedures are slightly similar to the adopted models in the proposed integrated framework in this study. However, since the adopted models in this study were academically well established and tested (as discussed before), no revision was applied to the system. In addition, there was not a mechanism in order to integrate those models (i.e. bid selection and also subcontractor evaluation) together as it is proposed in the current study. Thus the author did not carry out any revision on the system. Finally, they were very interested in the portfolio management mechanisms particularly KPI benchmarking and supply chain clustering.

It is worth noting that the comments received from practitioners who work in large scale projects both in Iran and in the UK i.e. UPP and Kayson are very close to each other. However, according to the comments from the Interserve Exeter Regional Office it seems that the proposed framework cannot be 100% practical but could be implemented partially.

In order to put the comments from the Interserve in relation with the limitations of usage of the system in small offices into the test, the final case study was planned in a SME construction company "Fanavaran" as it was introduced in Chapter 6. In the next section, the evaluation of the system conducted by the management team of this company will be explained.

7.4.2.4 Fanavaran's management team

According to the information illustrated in Chapter 5, Fanavaran is an SME in construction industry in Iran that works in the area of Architectural design, Engineering and EPC projects. Table 7.7 presents the positions of the informants in this case study.

Table 7.7 List of experts interviewed in Fanavaran Co.

Position	Education	Years of Experience
CEO	MSc Architecture	19
Head of projects Supervisory	MSc Civil Engineering	16
Financial Manager	BA Accounting	15

The management team of this company found the proposed system useful and practical. The details of the processes was explained and illustrated to the management team lead by the CEO. The feedback was provided as follows.

Regarding the subcontractor management subsystem, although the company was using a simple evaluation sheet consisting 6 general questions about time, cost and quality of performances of the subcontractors, they found the adopted subsystem in this study more comprehensive which covers their requirements better than their current practices. Automated bidding was deemed to be an interesting feature which supports the agile construction contracting by facilitating communication between subcontractors across the country. The supply chain configurator agent was the other module that was suitable for the managements. Since they were working with a number of suppliers for bank branch refurbishment projects, they found the model a useful tool for clustering best performance subcontractors in each province. This could lead to partnership agreements with the most resilient subcontractors who could do high quality projects in limited time windows. The management team scored the "Simplicity and practicality" of this subsystem, 10 out of 10 in the Likert scale evaluation sheet. In addition they had 90% confidence to usefulness of the proposed approach. However, they believed that it would require more time and resources to handle the data and interpret the results. They scored it 6 out of 10.

Fanavaran found the “Time-cost trade-off and Scheduling procedures” simple and practical with high level of clarity on methodology. Particularly, since CEO had confident knowledge and background in modelling and optimisation techniques coming from his MSc degree in engineering and also since he had published a number of journal and conference papers (CECTD, 2013), he was familiar with the methodology used. So he helped to transfer the idea by presenting the sample problem in the presentation meeting provided by me and facilitated understanding of the procedure by the other practitioners. They scored these two criteria 10 out of 10. Again they believed that the process was strongly useful and the quality of the results can support their businesses. They referred to the Khatam University project and advocated that if they had this tool six months ago they could better negotiate with Pasargad Bank and worked based on a concrete and clear contract and they would be able to appoint their dedicated subcontractors which would facilitate the collaborative work. So, the client’s representative would have not been allowed to deploy his subcontractors and they would face less conflict. Therefore the client’s representative would not be able to change some of subcontractors and cause problems for the company.

With respect to practicality, Fanavaran scored the adopted model for Bid selection, 5 out of 10 which is the weakest criteria in their evaluation questionnaire. The CEO explained carefully why they believe it is not so much practical for them. They believe that the emotional intuitive decision making approach that apply by members of the board is more practical than the adopted model. Particularly, they emphasised on the social networking and human being relationships in selecting the projects. The network of people who are interrelated to each other may lead the company to choose a project with high risk in hope of opening a future relationship with more important clients. Nevertheless, they acknowledged the quality and usefulness of the results by scoring it 8 out of 10. They also advocated that the clarity of the utilised methodology in this subsystem is high by ranking it 10 out of 10. In general, they said they like to use this method however it doesn’t mean that they will choose the results and final decision will be made by the CEO and other owners of the company.

Negotiation procedures with clients were the other aspects of the framework that discussed in details and they seemed to be fully attracted by the idea. They referred to the Khatam University project and adhered to use of CFP negotiation processes which potentially can help the contract conditions at the beginning of the projects. The CEO believes that since Fanavarán is an engineering and architecture based company, the combination of time-cost trade-off and CFP negotiation procedures could support the business as a powerful tool. Particularly, he referred to the cases when a client approaches the company who knows their previous projects. Since the client likes their design styles and asks for a unique and iconic building so, they can use different material and technology in their designs and provide a range of solutions to be chosen by their clients. This approach strongly improves the quality of negotiation based on different technology and material types which also affects project's makespan and total cost of the building based on each design. Utilising a powerful tool for providing several scenarios for the clients in design phase could potentially lead to taking the construction contract as well. The CEO suggested putting this approach in their ISO 9001:2008 procedures and using the process as quick as possible.

The last issues that were scrutinised by the management team of Fanavarán was KPI benchmarking and its associated rule models. They admired that although after finishing a project, there is a questionnaire that will be filled by the clients e.g. Pasargad Bank in order to receiving feedback of the quality of service, KPIs calculation was not been fully utilised so far. In addition, in Iran there is not an organisation similar to KPIzone (Centre for Construction Innovation, 2013) which is used for benchmarking purposes in this study. Therefore, they were conservatism for giving high rank to the practicality of this subsystem. Nevertheless, they acknowledge the idea and through brainstorming process suggested some thoughts for modification of the subsystem in order for adapting and making it suitable for use. The idea was to set some targets for each indicator on a yearly basis and to use the methods based on "construction excellence" procedures. It should be mentioned that the author advised the company to carry out an in-depth research study prior to implementing the KPI benchmarking procedure. This is based on the fact that KPI & Engine zone was developed for the UK construction

industry and might need some modification in order to comply with Iranian construction industry environment and the government regulations. The other option for adopting KPI benchmarking would be by the framework that was proposed by Bassioni et al. (2005). However, as he suggested in his “further research works” section, this framework needs to be studied deeper in order to be generalised for two aspects, for using it in international projects, as well as using it in small and medium sized enterprise SMEs.

Overall, three practitioners listed in Table 7.7 who collaborated in this case study, evaluated the proposed system as “very useful”. The collaboration between the researcher and the company has undergone full training and support. The average scores are presented in Table 7.8.

Table 7.8 The proposed model evaluated by Fanavaran Co.

Criteria for system evaluation	Simplicity and Practicality	Clarity of methodology	Time and resource consumption	Quality and Usefulness of the results
1- Subcontractor Management	10	10	6	9
2- Scheduling / Time-cost trade-off	10	10	6	9
3- Project selection and bid preparation decisions	5	10	10	8
4- KPI Rule models	6	10	7	8
Comprehensiveness of the Integrated system	8	10	8	9
Compare with existing approaches	8	10	8	9

It is worth noting that, their evaluation of “Clarity of methodology” was the highest score that the proposed framework has obtained compared to other case studies. There are two reasons for that. Firstly, they showed interest and put a lot of time to understand the details of the processes through several meetings and discussions. Therefore, they became fully familiar with the proposed framework. Secondly, two of them had MSc in Civil and Architectural engineering providing them with adequate background knowledge to understand entire model. The author also believes that one of the main reasons that they got enthusiastically involved in this case study was that Fanavaran Co. is a private ownership family based company. Therefore, they need to enhance themselves with new ideas and empower their

staff with new models and tools. The existing tools in project management market do not entirely cover the requirements of hierarchical project portfolio planning. Thus the CEO supported this collaboration which brought additional benefits for both the researcher and the company.

7.5 Overall evaluation and Discussion

In the previous sections the scores gained by each individual case study company were discussed. The main reason for considering company-oriented evaluation and discussion was that according to Aritua et al. (2009), the environment that a company works has a huge impact on strategic decisions which leads to determining the tactical decisions (see Figure 2.2). Therefore, paying attention to the context can be a valuable approach for understanding the validity of the proposed system framework. For instance, although Interserve's regional office in Exeter and Fanavaran are both categorised as SME companies, the scores obtained from these companies are totally different from each other. While Interserve Exeter works in a limited market in a small city like Exeter with a population of approximately 100,000, Fanavaran is located in Tehran and has a good access to the huge market of a capital city with a population over 12m. This provides a totally different environmental situation for Fanavaran. There are many subcontractors that are interested in working with this company while according to the Interserve management team in Exeter they struggle to find appropriate subcontractors who are able to prepare and submit their bids in a proper quality and in a short limited of time. They have to follow up a request for bid several times to obtain a reasonable bid from a qualified subcontractor. Therefore, they believed that the time-cost trade-off based on automated bidding process developed in this research was not relevant to their market. In contrast, Fanavaran gave the maximum score to this feature of the system.

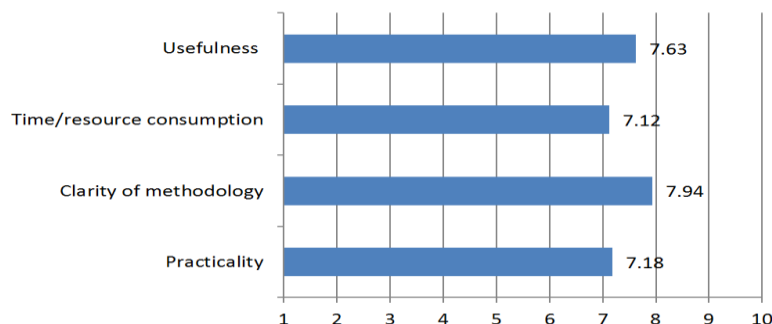
Thus, the context needs to be investigated and the advantages and disadvantages of the framework should be evaluated based on issues such as the availability of qualified subcontractors and the type and number of the potential clients i.e. market situation. However, regardless of considering the context, in this section the analyses are presented to understand how practitioners generally evaluate each individual features of the system and also the comprehensives of the framework.

As discussed in Section 7.4.2, the framework as a conceptual model for integrating operational, tactical and strategic decisions was rated according to the four criteria i) simplicity and practicality that refers to applicability, ii) clarity of the methodology, iii) time and resource consumption and also iv) usefulness.

Eleven full responses were collected from the interviews conducted in four companies. Considering the number of collected questionnaires, conducting statistical parametric analyses such as multivariate techniques or t- distribution that are based on the assumption of normality of the response distribution was not testable and therefore was not applicable (Van Belle, 2002; Bassioni et al., 2005).

However a nonparametric test was conducted to identify the equality of the mean values of the criteria on four categorised subsystems i.e. i) Subcontractor Management, ii) Scheduling/ Time-cost trade-off, iii) Project selection and bid preparation decisions and iv) KPI Rule models. Appendix E shows the result of the ‘Kruskal-Wallis’ test run by SPSS v.21. The results revealed that the mean of scores in all of the four subsystems on the criteria of ‘Simplicity and practicality’, ‘Clarity of methodology’ and also ‘Quality and usefulness of the results’ are the same where the Sig level of each criterion is 0.699, 0.663 and 0.408 respectively. However, for the criterion of ‘Time and resource consumption’ it indicated that the third subsystem i.e. ‘Project selection and bid preparation decisions’ has gained higher scores than the other subsystem. It means that the practitioners believed that the bid preparation/negotiation process is less time consuming than other subsystems. The response means of the criteria were calculated on an Excel sheet and are presented in [Figure 7.8](#).

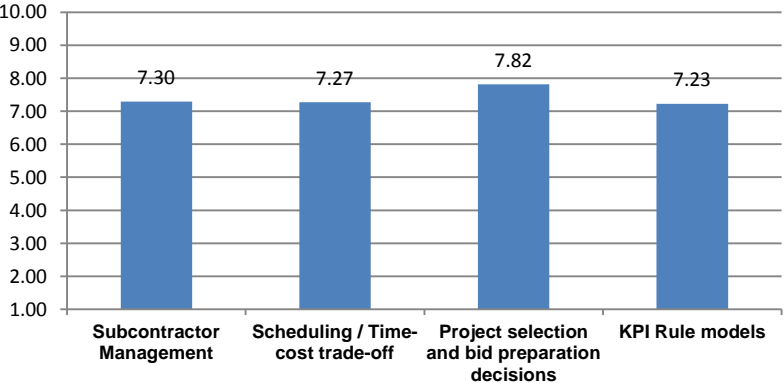
Figure 7.8 Overall evaluation of the proposed framework



Among these scores, the clarity of the methodology has the highest scores in comparison with others (average is 7.98 and standard deviation is 1.4). It implies that most of the practitioners actively engaged with what was presented in the interview sessions and understood the dimensions of the framework easily. This is another reason that why in the research methodology I chose the presentation of a prototype MAS-DSS software solution rather than asking them to read the IDEF work sheets. This method was more interactive and helped them to ask any questions during the presentation sessions resulted in the high level of understanding of the framework. In addition, usefulness of the framework gained the second highest average score (7.63). It means that if they make an effort to apply the proposed methods in this framework the results would be very valuable for hierarchical multi-project planning. The minimum score is given to the time and resource consumption with the average scores of 7.12. It refers to this fact that they need to do some more activities in comparison with their current efforts for implementation of the framework. However, still they are happy with the level of practicality of the system. It reflects that the communication protocol devised in the proposed system reduces the level of bureaucracy that normally a system in this scale needs to handle. In general, the analyses revealed that on average the framework is easy to apply, the methodology is very clear; it is an efficient method and the results would be very useful.

Since the entire of the system constitutes of the four main features, in Figure 7.9, the average means of the attained score in each subsystem are shown to present how much practitioners are satisfied from each individual subsystem.

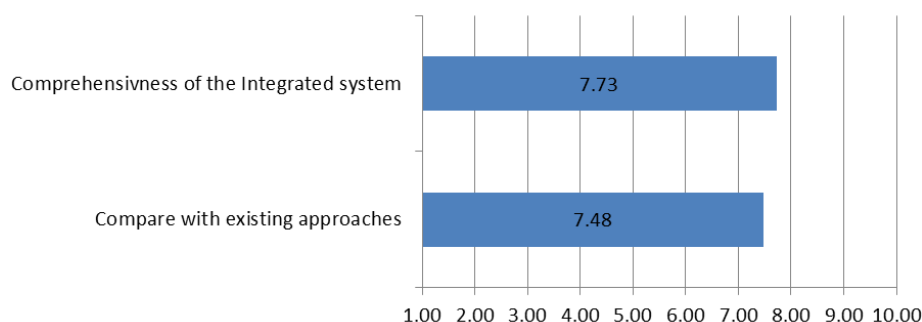
Figure 7.9 Overall evaluation across all the criteria for individual subsystems



The highest average calculated score is related to the 'project selection and bid preparation decisions' (7.82) as discussed earlier in this section. It clearly indicates that the bid preparation and negotiation methodology that was proposed in this study for the first time (see Sections 6.7.4) is highly acknowledged by the practitioners. Moreover, the second subsystem that gained the higher score is 'Subcontractor management' that constitutes subcontractor evaluation and selection, bidding communication and supply chain configuration. From the attained score, it is revealed that the existing lack of knowledge in these areas are fully satisfied by the methodology proposed in this research and the proposed integration among these interrelated processes received a good level of acceptance from practitioners with the average score of 7.3.

Finally, in two last questions of the questionnaire, respondents were asked to score the comprehensiveness of the model and also to compare the framework with what they currently conduct. In other words, the last question reflects the attitude of the practitioners to accepting the change in their management processes. Switching to a new system is the hardest activity in process reengineering methodology in enterprise system development. It needs a high rate of acceptance between different layers of organisation i.e. top management and operational team. In Figure 7.10, the above evaluated criteria were specifically investigated to understand in general how the framework can be substituted with their current practices. Considering the attained average score for 'Comprehensiveness of the integrated framework' (7.73) and also 'Comparing with existing approaches' (7.48) both are the evidence of the acceptance of the framework for implementation.

Figure 7.10 Overall evaluation for implementation



By observing the figures, it can be concluded that on average all the evaluation criteria are very or extremely acknowledged by the practitioners across the different sectors.

7.6 Summary

This chapter aimed to explain the evaluation process of the proposed framework and its counterpart MAS-DSS. The non-commercialised MAS-DSS software was developed and the designed features in this framework were partially implemented into the software. A verification phase was conducted by testing the results obtained from solving the data collected from the ongoing project in the first case study i.e. UPP. The results of the mathematical procedures discussed with UPP management team, compared well with their current practices and received a high level of acceptance. However due to confidentiality of data, the author was unable to publish the results. Nevertheless, qualitative feedback from UPP was discussed in this chapter. It should be noted that to verify the proposed optimisation method a test dataset was chosen from the literature and results compared previously in Section 6.7.3.1.

In addition, apart from UPP, four empirical evaluation case studies were conducted and the feedbacks attained from practitioners were discussed in detail. Since the selected case studies covered a range of national, international, large size and also SME companies, the validation process provided a deep and meaningful evaluation for the proposed framework.

In general, companies found the proposed model useful and practical. All of them were interested to carry on the collaboration for future implementations which discussions about is beyond the scope of this study. In brief, all the companies involved had confirmed the needs for full or partial implementation of the proposed framework. This was inferred as a result of the validation process conducted to contribute towards generalization of the proposed model.

CHAPTER 8 CONCLUSION

8.1 Introduction

In this research, a new framework for hierarchical multi-project management in the construction industry has been proposed and evaluated. This chapter is devoted to a discussion on the achieved objectives and how this model can facilitate decision making in the complex real world multi-project main contractor companies.

This discussion will be followed by recommendations for how the model can be implemented in the real world construction industry and study's limitations. The chapter will end with a conclusion and contributions to knowledge and further research recommendations.

8.2 Discussions

The management of the multiple projects and supply chain operations in the construction industry is known to be a very complex task. There are many research works with regard to managing the different processes in this industry such as project selection, bidding process, subcontractor selection, project scheduling and control and also performance management. Although these major business processes have been studied individually for many years, devising the hierarchical multi-project planning that integrates decision making at the operational, tactical and strategic levels has been neglected. In addition, the scarce available methodologies in hierarchical multi-project planning from other domains (Hans et al., 2007) are not suitable for use in the main contractor companies because they do not consider the uncertainty and complexity that exist in the construction industry.

Hans et al. (2007) advised that a hierarchical multi-project planning framework that is concerned with real world problem needs to be designed based on requirements of the targeted industry and should lead to developing a useful DSS tool.

In accordance with the above discussion, this study aimed at designing a practical framework for managing the multiple projects in main contractor companies. Similar to the work of De Boer et al. (1997) and De Boer (1998) who conducted a case study in RNND and devised a hierarchical planning framework and its associated tool for the ship repair industry, in this research the framework was devised based on findings from an in-depth case study conducted at UPP.

Hans et al. (2007) gave advice for fulfilling the pitfalls of De Boer's (1998) study. In contrast with De Boer (1998) which ignored the existing uncertainty in the context and supposed that the resources are fully under the control, this research aimed at addressing the uncertainties and complexity of the decision making system which are related to collaboration between several autonomous actors such as clients, main contractor management team and subcontractors. While De Boer (1998) proposed a DSS solution for deterministic multi-project scheduling, in this research an MAS-DSS model was constructed to facilitate communication, collaboration and decision making in three levels of a hierarchical framework as shown in Figure 6.1. The required modules for each level of hierarchy were adopted from available methodologies in the literature or were developed by the researcher if they were not available. These are summarised in Figure 6.9.

To propose an integrated hierarchical framework, five objectives were devised which in shortened form are:

1. Investigate existing methods in hierarchical multi-project management
2. Identify the interactions and relationships between parties
3. Investigate integration possibilities across the hierarchy
4. To construct a framework for practical strategic, tactical and operational decisions in construction multi-project management and to adapt the required decision making procedures for the constructed framework
5. Validate the feasibility of the proposed approach

The study achievements in reflection of the objectives are as follows:

8.2.1 Investigate existing methods

The construction industry is identified as a highly fragmented industry in comparison with other sectors. The projects are highly time-consuming and geographically scattered. Different parties are involved in each project and interact in order to achieve the contract objectives. Thus, the management teams in contractor companies are concerned with highly uncertain, dynamic and complex decisions. They are involved with several decisions that are related to short, medium and long term planning horizons. At the operational level, they deal with project scheduling, controlling the progress of ongoing projects and rescheduling them if it is required. At the tactical level, bid/project selection and bid preparation are exhaustive activities under the responsibility of portfolio manager. Beside those, at the strategic level, decisions such as supply chain configuration and partnership agreements are among the critical decisions that should be made by the management team. These three decision making levels are dynamically interrelated together which are influenced by the feedback received or perceived from the market environment, competitors' situations and the impact of the company on its entire supply network.

Conducting an in-depth case study in large scale building projects for more than 11 months gave a valuable opportunity to identify the practitioners' requirements particularly for negotiating with clients to achieve the contracts in a very competitive market with recessions and long periods of sleep time. It was also revealed that they need proper tools and techniques for dealing with subcontractors who are distributed geographically and have different levels of competence and expertise, in the highly fragmented construction industry. It showed that communication and collaboration play a critical role in enterprise success. Comparing these requirements with the existing knowledge in the literature shed light upon the gap between theory and practice in different layers of the hierarchical multi-project planning. It was revealed that despite much research in each individual managerial decision making layers, not only the contractor companies but also the construction management literature suffer from a lack of existing integrated tools and techniques to deal with the complexity of the multi-project planning and supply chain management in a holistic approach. This caused

sleep times between projects so that actors try to find their short term objectives rather than long term partnership collaboration.

Therefore, based on these investigations, a hierarchical multi-project management framework is identified as a vital need. This framework should facilitate the collaborative work through communication across the fragmented industry, interactively optimising the project schedules in which the clients' targets in relation with time, cost and other criteria will be met.

The framework has been developed and is shown as Figure 6.1. This is an original and clear framework for this research that can also be used for further research in the area of multi-project planning and supply chain configurations.

8.2.2 Identify relationships and interactions between parties

The case studies and literature reviews revealed that several autonomous decision makers including clients and subcontractors (as external actors) and also project managers and a portfolio manager (as internal actors) are the four main actors in this context. This generates a lot of uncertainty, variability, ambiguity that makes decision making systems so complex. In this research for the first time a complex dynamic system which presents the relationships and interactions between these autonomous actors was developed. This is shown in Figure 6.3.

8.2.3 Investigate integration possibilities

According to the literature review that covered project management, supply chain management, manufacturing systems and multi agent systems, the multi agent system architecture is identified as a valid methodology to facilitate communication between aforementioned autonomous agents and to integrate decentralised decision making in different hierarchical levels.

A multi-agent architecture for the complex multi-project planning and supply chain management is set out for the first time in

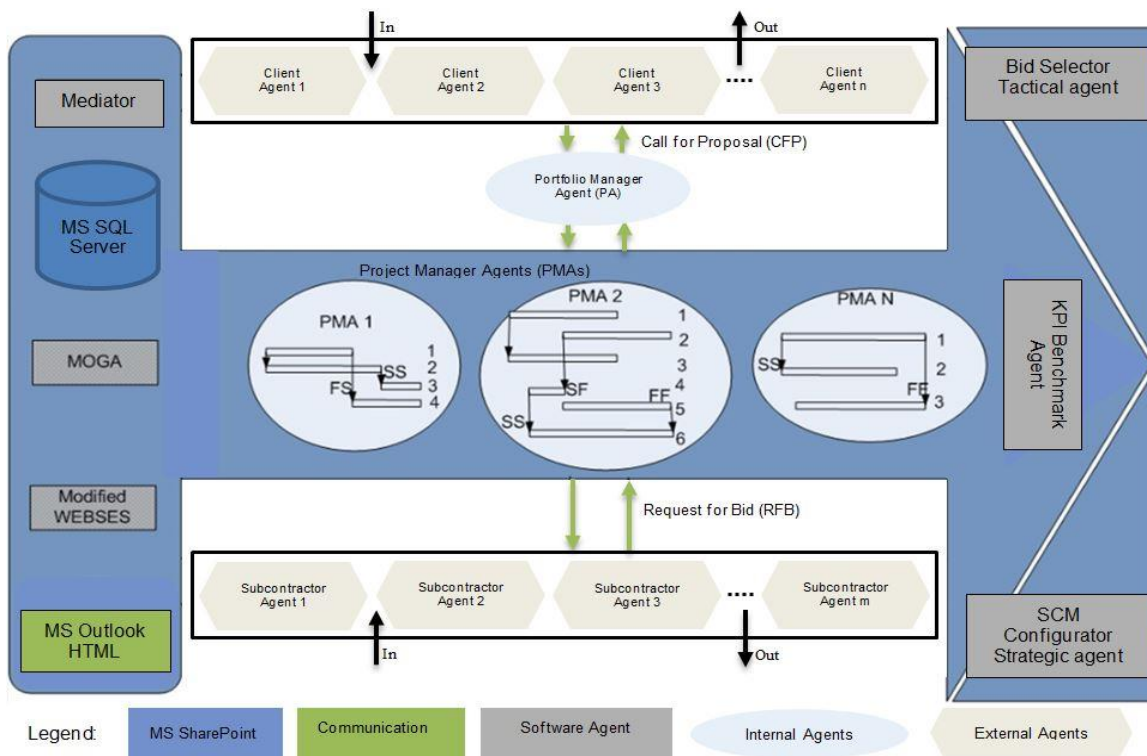


Figure 6.2 which provides a basis for information systems design for the construction industry.

8.2.4 Construct framework and adapt the decision making procedures

The hierarchical multi-project management framework is constructed and presented in Figure 6.1 in order to fulfil the requirements that were identified from the case studies. The framework utilised multi agent system architecture as

presented

in

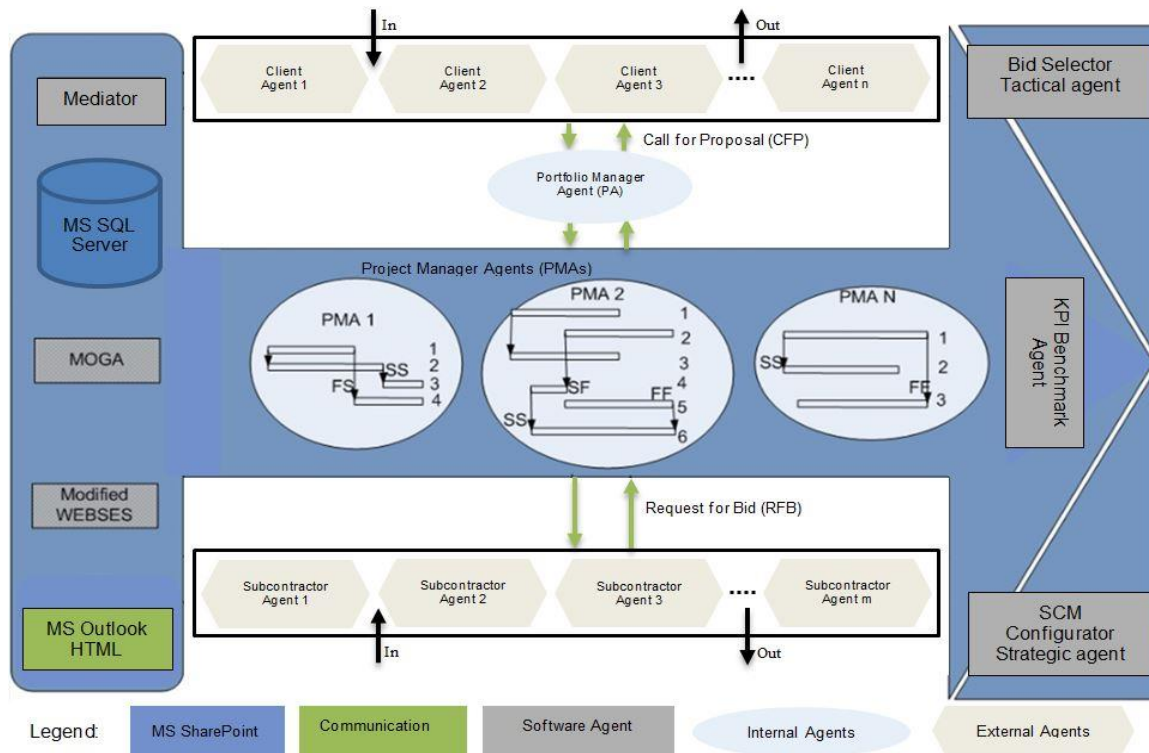


Figure 6.2 in which several physical and artificial agents interact and communicate to achieve collaborative working in construction industry as shown in Figure 6.3.

The procedures that were adopted are chosen from the literature and required modifications are made to establish the dynamic integration across the framework so that short, medium and long term planning horizon decision making can be managed. The proposed framework was initially devised based on in-depth case study in the construction industry. Project optimisation used time-cost trade-off followed by multi attribute utility theory (MAUT) to facilitate project scheduling, subcontractor selection and bid negotiation with client while qualitative methods were used for bid risk assessments and subcontractor evaluation. Main contractor companies can use the proposed methodology to integrate their decisions across geographically dispersed projects where different project managers autonomously manage their projects and the associated project supply chain. In addition, the portfolio manager globally controls the entire portfolio and the associated enterprise supply chain through KPI benchmarking. The integrated framework facilitates organisational learning using lessons learned across the enterprise projects through sharing project managers' experiences and knowledge.

8.2.5 Validate the feasibility of the proposed approach

In order to validate the proposed framework several actions were made. The mathematical procedures are partially verified and tested by the real data gained from in-depth case study (see Section 7.3) and also test data obtained from the test cases (see Sections 6.7.3.1, 6.7.4).

To evaluate the usefulness and applicability of the proposed framework a prototype multi agent system-decision support system (MAS-DSS) was developed to facilitate feedback from practitioners (see Sections 7.2 and 7.3). The proposed framework was evaluated empirically. The dynamic integration and also communication platform proposed in this study provides a suitable decision support system that was welcomed by the practitioners in five different construction companies. The internal evaluation (see Section 7.4) along with four external validation case studies (see Section 7.5) were national and international, large size and SMEs construction companies which provided a confident evaluation. In total, 15 experts were involved in the evaluation process with average 20 years working experience in large construction projects. The feedback gained from these case studies strongly supported its industrial acceptance (see Section 7.5). So the proposed framework is suggested to be used to close the gap between theory and practice.

8.3 Major contribution and overall evaluation

In this research, the author took the advantage of using multi agent system design architecture (Brenner et al., 1998) to construct the integrated framework and its MAS-DSS tools for multi-project management in construction industry. The hierarchical multi-project planning and control framework introduced by Hans et al. (2007) was the major guideline for this research and the author endeavoured to construct an applicable and useful framework for managing the complexity of multi-project planning and control in main contractor organisations. Looking at the literature, the author identified the recent developments in the different processes in single project planning. In relation to multi-project management there were ample studies in the literature review. Although the need for knowledge management and use of information technology in “distributed organisational memory” (Robey et al., 2000) and also organisational learning and use of lessons-

learned in distributed and dispersed construction projects have been discussed in the literature (see (Tennant & Fernie, 2013) and (Atkinson et al., 2006)) to the best of the author's knowledge there was not an applicable tool that enables the contractor companies to capture these notions in a practical way.

The literature review revealed that Aritua et al.'s (2009) research was among the few studies that highlighted the complex adaptive system perspective of the multi-project construction clients. They exhibited the relation between strategic and tactical decisions in construction companies, highlighted negative and positive feedbacks from lessons learned and called for study in the field of complex adaptive systems to manage multi-project portfolios in the construction industry. Their study was limited to discussing the concepts, requirements and the existing complexity in the context rather than proposing an applicable framework for handling the complexity and managing the required processes. In addition, like Xue et al. (2010), they recommended supply chain management and long term partnerships as the best approach for multi-project management. Neither proposed any practical solution in order to link subcontractor evaluation processes at the single project level to the supply chain configuration at enterprise level.

Thus the major contribution of the present study is that for the first time the complex multi-project planning and control system management and its supply chain operations both at the project level and at the enterprise level have been tackled and the integrated framework has been derived. Although some of the adopted components of the proposed framework were well known in the context of project planning and scheduling, the dynamic integration of the hierarchical planning and control system and the communication platform proposed in this study provide a suitable decision support system that has been warmly welcomed by practitioners who work in four different construction companies.

The companies used for empirical evaluation were national and international operators from large scale to SMEs. The positive feedback received from them shows the practicality and usefulness of the MAS-DSS for commercialising the proposed model. This will be discussed in the next section.

8.4 Recommendations for industry

As discussed above, the purpose of the present research was to construct a hierarchical decision making framework that enables construction companies to accommodate the existing complexity in the real world context. The framework is constituted of several interrelated procedures. Along with the proposed framework a MAS-DSS prototype system was developed to assess the applicability, practicability and usefulness of the proposed framework. The researcher utilised this prototype MAS-DSS solution to illustrate the procedures and mechanisms that were adopted in the entire framework to the practitioners. So the case study companies were able to make sense of a real fully developed solution and its associated advantages. The evaluation process was made in a reasonable time for all case study companies and the invaluable feedback that strongly supports the usefulness of the proposed integrated planning framework was obtained. However, the developed MAS-DSS solution is just a prototype version. To implement the full version of the system architecture, a software development team is required to develop, test and verify the entire enterprise solution particularly with respect to data security issues. Since the proposed model includes highly sensitive and confidential information from companies that work in a competitive environment, the security of information is an important challenge that needs to be addressed in a software development research project towards commercialising the proposed model which is beyond the boundaries of this research.

Finally, with respect to integration with KPI Engine & Zone, there is a need for further investigation into the mechanism by which this model can be linked to that website. Moreover, the two proposed KPI rule models and their parameters can be compared with the previous projects in a particular case study company in order to be modified and updated based on experimental tests.

8.5 Limitations

In this study, the empirical evaluation was based upon four enterprises dealing with multi construction projects of national and international firms and achieved high level of acceptance among them. Nevertheless, the experts' perceptions and

feedback are certainly limited to those companies and does not represent all the construction companies across the world. Further research should show whether the findings can be generalised across the construction industries and are matched with other countries' contract laws.

In addition, as it was mentioned in Section 7.4.2, the usage of KPI Engine & Zone is limited to companies in the UK. Therefore, the suggestions discussed in that section should be applied for the use of benchmarking subsystem in other countries.

The supply chain configuration procedure, based on a probability clustering model has been tested in MTS environment by Akanle & Zhang (2008). However, to deal with the temporary nature of construction projects, some changes were implemented. Since information for test was not available, this sub-system was not thoroughly tested mathematically and evaluation was limited to the experts' perception based on suggestions made by Gadde & Dubois (2010). However, the rationality and realism of the suggested clusters is discussed with practitioners and found positive feedback which shows that it is in conformity with Gadde & Dubois's (2010) study.

Finally, the proposed bidding negotiation procedures described in Section 6.7.4 have gained much attention from experts who work in private markets particularly in building projects. However, for large infrastructure projects such as oil and gas, transportation etc. they believed that according to the current market situation, the public sector is trying to reduce the costs and there is no room for negotiation with the clients. So, for those projects, other alternative methods should be investigated instead of the time-cost trade-off problem which satisfied the requirements of the bidding process at the present study.

8.6 Conclusion and contribution to knowledge

This research makes the following original contributions to knowledge in the field of hierarchical multi-project management for the construction industry, which is characterised by high uncertainty, fragmentation, complex decisions, dynamic changes and long-distance communication.

1. This work allows the different processes in this industry such as project selection, bidding process, subcontractor selection, project scheduling and control and performance management to be collected into an integrated framework that integrates decision making at the operational, tactical and strategic levels.
2. This novel framework conceptualises the problem in an original way that allows the project management activities to be operated using a DSS with additional communication which facilitates collaboration.
3. The proposed method in this work allows practitioners to handle the automated bidding, subcontractor evaluation and project scheduling in an integrated manner to achieve the best combination of subcontractors for the project level. This is an original contribution in configuring and scheduling the supply chain of each project at the same time.
4. The integrated model provides a new way to allocate resources and schedule concurrent projects while resource conflicts are removed by appointing more reliable subcontractors to the more risky projects and also controlling the risk of over deploying subcontractors across the distributed projects.
5. This work provides a method of continuous adaptation by connecting the performance measurement data with the strategic decisions to manage the complexity of the multi-project environment and to promote collaboration with high performing suppliers.
6. The integrated framework developed by this research facilitates organisational learning and using lessons learned across the enterprise projects through sharing project managers' experiences and knowledge from different sites. Particularly their experiences in using subcontractors and also their project KPIs will be shared and revealed for other project managers and can lead to improvements across the portfolio.
7. The framework allows a portfolio manager to configure the supply chain for the whole portfolio rather than each individual project. In other words, for the first time, using the probability clustering methodology in the construction

supply chain, clusters suppliers into teams that have worked well together. This should lead to expanding the main contractor market share and reducing the sleep time between projects.

8.7 Future research

According to the present research achievements, some other issues are available and need to be addressed for future research as follows:

The required ontology for linking the MAS-DSS to the KPI Engine & Zone website needs to be developed for full implementation of the commercialised version of the proposed MAS-DSS enterprise solution.

Future work could incorporate more risk mitigation procedures in other aspects of the portfolio along with those models that were adopted in this study.

At the project optimisation level, in this research time and cost were two objectives that were considered. Another model could be adopted in order to consider other objectives such as maximising quality and maximising safety. It should be noted that although considering these objectives seems to be a fruitful academic study in this research area, as it is identified in empirical study, the applicability and usefulness of the model will be far from the practitioner's perceptions.

It would be interesting to incorporate the proposed framework with Building Information Modelling (BIM) (Succar, 2009) which is a process framework representing both graphical and non-graphical aspects of the full building life cycle. Thus the available geometric and geographic information of the building and its components specifications in a repository of BIM can feed into the proposed model in this research and improve interoperability across the unstructured supply chain and can extend the model to procurement and ordering management systems. This claim is also in line with the call for further research work in BIM as discussed by Lenin (2011) and Tennant and Fernie (2013).

It may be possible in future to incorporate the proposed framework with ERP solutions aiming at integrating more operational decisions such as financial management and human resource management. One other aspect that needs to be addressed for this incorporation is to devise the required ontology for

connecting and transferring information between the ERP systems and the present research work.

Social network analysis (SNA) is other viable research area that can be studied in relation with construction multi-project management. Particularly the role of each individual project manager can be investigated in shaping a strong project supply chain. In the same vein the role of project portfolio manager within the enterprise can be analysed and their positions within the social network can be addressed to identify how this can affect the decision making that was considered in this study.

It is hoped that this work will provide a sound basis leading to an integrated program of research and software development that will result in improved decision-making, efficiency and sustainability in the construction industry of the future.

Appendix A

Non-dominated sorting genetic algorithm (NSGA2)

A.1 Introduction	235
A.2 Fast Non-dominated Sorting Approach.....	235
A.2.1 Density Estimation	237
A.2.2 Crowded comparison operator.....	238
A.2.3 Main Loop	238

A.1 Introduction

NSGA2 is a generalization of the genetic algorithm (GA) for multi objective optimization (MOO). Similar to the single objective GA (SOGA), it is based on a simulation of natural selection and population genetics. It needs three main functions for each generation namely selection, combination and mutation where each chromosome represents a certain solution (Goldberg, 1989). In contrast with SOGA, there is a set of non-dominated solutions in MOO, where none of the members dominate the others. A particular solution is said to 'dominate' the other solution in the population if it is at least as good as the latter in every dimension and better in at least one dimension (objective). NSGA2 is a fast approach for ranking the non-dominated solutions. It also calculates a measure known as 'crowding distance' for each solution (Deb et al., 2002). At the selection stage, both rank and crowding distance are used to generate a new population. In each iteration fitness functions are calculated to provide relevant information for the ranking stage. The iterations are terminated if a predetermined number of generations have been computed. In this work, NSGA2 was used to develop a Pareto-front curve that shows the best solutions compromising between cost and time. In this section, an explanation is given for how NSGA2 works.

The NSGA2 has the following properties:

1. It emphasizes the non-dominated solutions by ranking them to different categories. A fast nondominated sorting procedure is utilized for this purpose.
2. It uses an elitist principle; since all previous and current population members are included in the selection operator, elitism is ensured.
3. It uses an explicit diversity preserving mechanism; to ensure the global optimization. A fast crowded distance estimation procedure and a simple crowded comparison operator were utilized for this purpose.

These properties will be explained in the next two subsections and finally the main loop of the algorithm will be described.

A.2 Fast Nondominated Sorting Approach

In NSGA2 two entities need to be calculated:

- (i) domination count n_p , the number of solutions which dominate the solution p ;

(ii) S_p , a set of solutions that the solution p dominates.
 The solutions with $n_p = 0$ represent the first non-dominated front. Then, for each solution with $n_p = 0$ (thus from the first non-dominated front), each member (q) of its set S_p is visited and its domination count is reduced by one (i.e. removes solution p from n_q).

For any member for which domination count becomes zero ($n_q = 0$), the member is put in a separate list Q . Therefore, Q represents the second domination front.

These procedures are repeated for each member of Q to identify the third, fourth and so that all fronts are identified. The pseudo code of the ranking process is presented in Figure A.1. The ranks can be determined and sorted from the best rank to the worst one. Figure A.2 demonstrates a graphical illustration of the three ranks for the assumed time-cost trade-off solutions.

```

fast-non-dominated-sort( $P$ )
for each  $p \in P$ 
   $S_p = \emptyset$ 
   $n_p = 0$ 
  for each  $q \in P$ 
    if ( $p \prec q$ ) then
       $S_p = S_p \cup \{q\}$ 
      else if ( $q \prec p$ ) then
         $n_p = n_p + 1$ 
    if  $n_p = 0$  then
       $p_{\text{rank}} = 1$ 
       $\mathcal{F}_1 = \mathcal{F}_1 \cup \{p\}$ 
   $i = 1$ 
  while  $\mathcal{F}_i \neq \emptyset$ 
     $Q = \emptyset$ 
    for each  $p \in \mathcal{F}_i$ 
      for each  $q \in S_p$ 
         $n_q = n_q - 1$ 
        if  $n_q = 0$  then
           $q_{\text{rank}} = i + 1$ 
           $Q = Q \cup \{q\}$ 
     $i = i + 1$ 
     $\mathcal{F}_i = Q$ 

```

Figure A.1 Pseudo-code to nondominated sorting procedure (Deb et al., 2002)

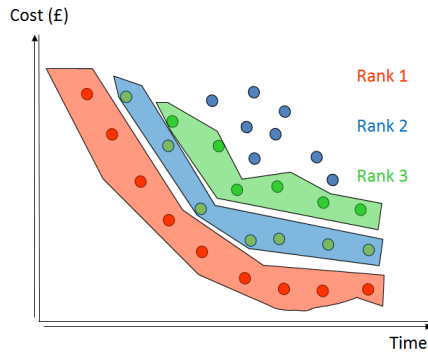


Figure A.2 Nondominated ranks (Keedwell, 2012)

A.2.1 Density Estimation

To obtain a density estimation of solutions surrounding a particular solution, the average distance of two points on either side of the point along each of the objectives needs to be computed. This quantity $i_{distance}$ serves as an estimate of the perimeter of the cuboid formed by using the nearest neighbors as the vertices (this is the crowding distance). Figure A.3 shows the crowding-distance of the i^{th} solution in its front (marked with filled circles) the average side length of the cuboid (shown with a dashed box).

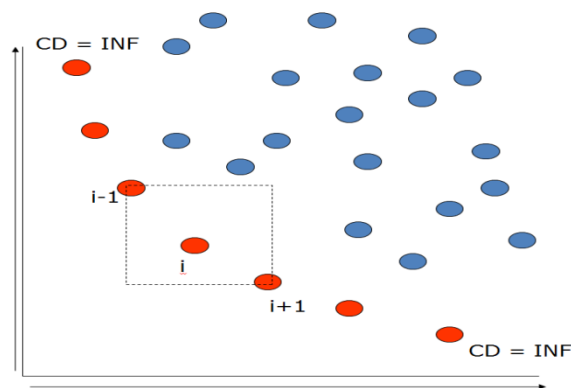


Figure A.3 Crowding –distance calculation. Points marked in red circles are solutions of the same non-dominated front (Keedwell, 2012)

The following algorithm is used to calculate the crowding-distance for each point in set I :

1. Call the number of solutions in I as $l = |I|$. For each i in the set, first assign $I[i]_{distance} = 0$;
2. For each objective m , sort the set in ascending order;
3. For each objective m , assign a large distance to the boundary solutions, or $I[1]_{distance} = I[l]_{distance} = \infty$, and for all other solutions $i = 2$ to $(l - 1)$, assign

$$I[i]_{distance} = I[i]_{distance} + \frac{I[i+1]_m - I[i-1]_m}{f_m^{max} - f_m^{min}}$$

Therefore, in order to compute the crowding-distance, the population first needs to be sorted in ascending order for each objective. Then for each objective function boundaries are set to infinity, and for all other (intermediate) solutions the distance is the absolute normalized difference in the function values of two closest solutions. This is repeated for all other objectives. The overall crowding-distance value is calculated as the sum of individual distance values corresponding to each objective, with each objective being normalized. The pseudo code of the procedure is presented in Figure A.4

Where the f_m^{max} and f_m^{min} are the maximum and minimum values of the m^{th} objective function.

```

crowding-distance-assignment( $\mathcal{I}$ )
 $l = |\mathcal{I}|$                                 number of solutions in  $\mathcal{I}$ 
for each  $i$ , set  $\mathcal{I}[i]_{distance} = 0$         initialize distance
for each objective  $m$ 
     $\mathcal{I} = \text{sort}(\mathcal{I}, m)$                 sort using each objective value
     $\mathcal{I}[1]_{distance} = \mathcal{I}[l]_{distance} = \infty$     so that boundary points are always selected
    for  $i = 2$  to  $(l - 1)$                     for all other points
         $\mathcal{I}[i]_{distance} = \mathcal{I}[i]_{distance} + (\mathcal{I}[i+1]_m - \mathcal{I}[i-1]_m) / (f_m^{max} - f_m^{min})$ 

```

Figure A.4 Pseudo-code to crowding-distance calculation (Deb et al., 2002)

A.2.2 Crowded comparison operator

The crowded comparison operator \prec_n ensures a uniform spread of the Pareto front during the various stages of the algorithm. Assuming that every individual i has the following two attributes: non-domination rank (i_{rank}), and crowding distance ($i_{distance}$). Then the partial order is defined as:

$$i \prec_n j \text{ if: } (i_{rank} \prec_n j_{rank}) \text{ or } ((i_{rank} = j_{rank}) \text{ and } (i_{distance} > j_{distance}))$$

This means that, between two solutions in the same rank category, the one with lower density or the one furthest from the others will be selected.

A.2.3 Main Loop

An initial random parent population is generated and sorted based on the nondomination criteria. Each solution is assigned a fitness (or rank) equal to its nondomination level (1 is the best level, 2 is the next-best level, and so on). An

offspring population Q_0 of size N is then created by the use of binary tournament selection, crossover, and mutation operators. In binary tournament selection two solutions are picked up from the population and the better solution is chosen.

After initialisation, the algorithm is based on the following steps:

1. A combined population is constructed $R_t = P_t \cup Q_t$. The size of the new intermediate population is $2N$.
2. The population R_t is sorted according to the nondomination sorting algorithm. Now, solutions belonging to the best nondominated set F_1 are of best solutions in the combined population and are highlighted more than the rest of the members in the combined population P_{t+1} . If the size of F_1 is smaller than N , all members of the set F_1 for the new population are opted. The remaining members of the population P_{t+1} are chosen from subsequent nondominated fronts in the order of their ranking.
3. This procedure is continued until no more sets can be accommodated. Say that the set F_l is the last nondominated set beyond which no other set can be accommodated. In general, the count of solutions in all sets from F_1 to F_l would be larger than the population size.
4. To re-achieve the population size N exactly, the solutions of the *last* front F_l are sorted by using the crowded-comparison operator \prec_n in descending order and the best solutions needed to fill all population members N are chosen

The new population P_{t+1} of size N is now used for selection, crossover, and mutation to create a new population Q_{t+1} of size N . The procedure of the NSGA-II is also shown in Figure A.5. In addition the pseudo code of the main loop is presented in Figure A.6. It is worth emphasising that although in the initialisation process and in the first generation, binary tournament selection is utilized, in any other generation, the selection is based on the crowded-comparison operator (Crowded Tournament).

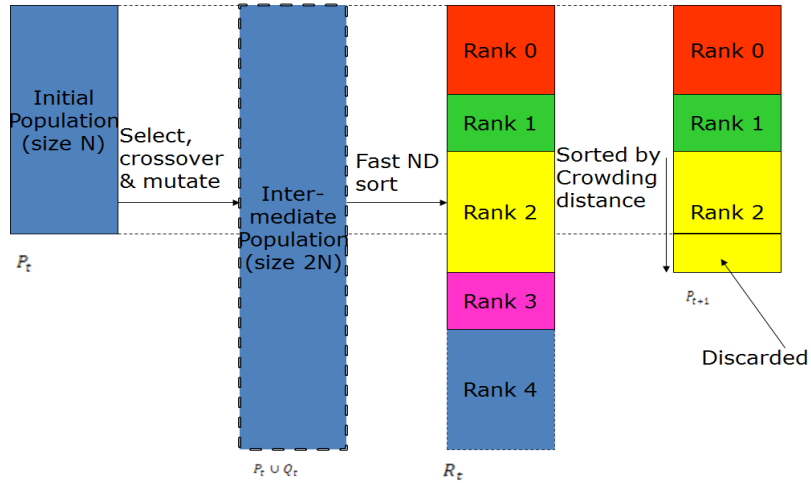


Figure A.5 NSGA2 procedure (Keedwell, 2012)

$R_t = P_t \cup Q_t$	combine parent and offspring population
$\mathcal{F} = \text{fast-non-dominated-sort}(R_t)$	$\mathcal{F} = (\mathcal{F}_1, \mathcal{F}_2, \dots)$, all nondominated fronts of R_t
$P_{t+1} = \emptyset$ and $i = 1$	
until $ P_{t+1} + \mathcal{F}_i \leq N$	until the parent population is filled
crowding-distance-assignment(\mathcal{F}_i)	calculate crowding-distance in \mathcal{F}_i
$P_{t+1} = P_{t+1} \cup \mathcal{F}_i$	include i th nondominated front in the parent pop
$i = i + 1$	check the next front for inclusion
Sort(\mathcal{F}_i, \prec_n)	sort in descending order using \prec_n
$P_{t+1} = P_{t+1} \cup \mathcal{F}_i[1 : (N - P_{t+1})]$	choose the first $(N - P_{t+1})$ elements of \mathcal{F}_i
$Q_{t+1} = \text{make-new-pop}(P_{t+1})$	use selection, crossover and mutation to create
	a new population Q_{t+1}
$t = t + 1$	increment the generation counter

Figure A.6 Pseudo code to the main loop of NSGA2 (Deb et al., 2002)

Appendix B

Hans et al.'s (2008) model


Project /Bid Risk Assessment Sheet

Project code:

Evaluator:

Project title:

Date:

Group	W	Description	Bad				Good
1		Project characteristics and importance					
1.1		Desirable contract forms and specifications	1	2	3	4	5
1.2		Project scale	1	2	3	4	5
1.3		Availability of production technology	1	2	3	4	5
1.4		Project environment and condition such as resource delivery and procurement system	1	2	3	4	5
1.5		Field conditions and accessibility	1	2	3	4	5
1.6		Desirability and social consensus on the project	1	2	3	4	5
1.7		Adequacy of contractual duration	1	2	3	4	5
1.8		Established relationship and reputation of owner	1	2	3	4	5
1.9		Importance of market share	1	2	3	4	5

2		Level of bid competition and market condition					
2.1		Condition/requirement of PQ (pre-qualification)	1	2	3	4	5
2.2		Type of bidding competition	1	2	3	4	5
2.3		Adequacy of the provided bidding preparation period	1	2	3	4	5
2.4		Number of potential competitive firms	1	2	3	4	5
2.5		Adequacy of prior bid information	1	2	3	4	5
2.6		Need for work	1	2	3	4	5

3 Degree of potential profit

3.1		Mean profitability of previous similar projects	1	2	3	4	5
3.2		Possibility of failure of previous similar projects	1	2	3	4	5
3.3		Degree of required return	1	2	3	4	5
3.4		Credibility and stability of funds	1	2	3	4	5
3.5		Roughly estimated profit	1	2	3	4	5

4 Contractor's position in bidding and ability to perform

4.1		construction technology's ability to perform	1	2	3	4	5
4.2		Firm's current resources including technical expertise and skilled personnel	1	2	3	4	5
4.3		Adequacy of financing capability	1	2	3	4	5
4.4		Capacity of market share	1	2	3	4	5
4.5		Familiarity and experience with the work	1	2	3	4	5
4.6		Current workload	1	2	3	4	5

5 Degree of representing risk exposures

5.1		Business environment of host country	1	2	3	4	5
5.2		Geography and climate conditions	1	2	3	4	5
5.3		Government acts and regulation	1	2	3	4	5
5.4		Degree of hazard and security	1	2	3	4	5
5.5		Quality of bid documents	1	2	3	4	5
5.6		Conditions of resource supplies and procurements	1	2	3	4	5
5.7		Capability of local subcontractors and vendors	1	2	3	4	5
5.8		Attitude toward foreign firms	1	2	3	4	5
5.9		Local customs and culture	1	2	3	4	5

Appendix C

Arslan et al.'s (2008) model Subcontractor Evaluation Sheet

Project code:
Subcontractor
code:

Project title:
Subcontractor name:

Date
Trade:

Group	W	Description	Unsatisfactory ← → Satisfactory									
A Cost												
A.1		Financial capacity	1	2	3	4	5	6	7	8	9	10
A.2		Timely payments to labourers	1	2	3	4	5	6	7	8	9	10
A.3		Completion of job within the budget	1	2	3	4	5	6	7	8	9	10
B Quality												
B.1		Quality of production	1	2	3	4	5	6	7	8	9	10
B.2		Standard of workmanship	1	2	3	4	5	6	7	8	9	10
B.3		Team efficiency	1	2	3	4	5	6	7	8	9	10
B.4		Quality of materials used	1	2	3	4	5	6	7	8	9	10
B.5		Experience in similar works	1	2	3	4	5	6	7	8	9	10
B.6		Experience in the construction industry	1	2	3	4	5	6	7	8	9	10
B.7		Job safety	1	2	3	4	5	6	7	8	9	10
B.8		Personal training	1	2	3	4	5	6	7	8	9	10
B.9		Number of qualified personnel	1	2	3	4	5	6	7	8	9	10
C Time												
C.1		Accessibility to the firm	1	2	3	4	5	6	7	8	9	10
C.2		Time accuracy in submitting bids	1	2	3	4	5	6	7	8	9	10
C.3		Completion of the job within the time	1	2	3	4	5	6	7	8	9	10
C.4		Adherence to programme	1	2	3	4	5	6	7	8	9	10
D Adequacy												
D.1		Proposal accuracy	1	2	3	4	5	6	7	8	9	10
D.2		Adequacy of experienced site supervi. staff	1	2	3	4	5	6	7	8	9	10
D.3		Adequacy of labour resources	1	2	3	4	5	6	7	8	9	10
D.4		Adequacy of material resources	1	2	3	4	5	6	7	8	9	10
D.5		Adequacy of equipment	1	2	3	4	5	6	7	8	9	10
D.6		Care of work & workers	1	2	3	4	5	6	7	8	9	10
D.7		Compliance with site safety requirements	1	2	3	4	5	6	7	8	9	10
D.8		Compliance with contract	1	2	3	4	5	6	7	8	9	10
D.9		Compliance with company image	1	2	3	4	5	6	7	8	9	10

Appendix D

Validation Sheet

Validation Sheet

The management of the complex project portfolio planning and supply chain operations
 This sheet is designed to validate the Framework/ system proposed by the research at the University of Exeter

		Name	Company	Position		
		Date				
Criteria for system evaluation	Simplicity and Practicality	Clarity of methodology	Time and resource consumption	Quality and Usefulness of the results		
	Not practical=1 ↕ Easy to apply=10	Too Vague=1 ↕ Ver Clear=10	Too Much=1 ↕ Very efficiente=10	Unuseful=1 ↕ Very usefull=10		
Subsystems						
1- Subcontractor Management	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10		
2- Scheduling / Time-cost trade-off	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10		
3- Project selection and bid preparation decisions	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10		
4- KPI Rule models	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10		
Comprehensiveness of the Integrated system	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10		
Compare with existing approaches	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10		

1- Including: Subcontractor Evaluation, Bidding process and communication, Subcontractor Selection and ultimately Supply Chain configuration

2- Including: Planning and Scheduling, Time-cost trade-off, Rescheduling negotiation protocol

3- Including: Risk assessment of the CFP, Negotiable projects, CFP is based on competitive bidding

4- Including: KPI calculation, KPI control rules for project selection, KPI control rules for Supply Chain Configuration

Please advise any comments:

Appendix E

Nonparametric test

NPar Tests

[DataSet1] \\isad.isadroot.ex.ac.uk\UOE\User\Desktop\Case Study data Al eza Pakgohar.sav

Kruskal-Wallis Test

Ranks

	Features	N	Mean Rank
Simplicity and Practicality	1.00	11	22.86
	2.00	11	26.05
	3.00	11	21.00
	4.00	11	20.09
	Total	44	
Clarity of methodology	1.00	11	21.50
	2.00	11	20.05
	3.00	11	26.36
	4.00	11	22.09
	Total	44	
Time and resource consumption	1.00	11	17.00
	2.00	11	20.55
	3.00	11	32.50
	4.00	11	19.95
	Total	44	
Quality and Usefulness of the results	1.00	11	24.23
	2.00	11	19.05
	3.00	11	26.82
	4.00	11	19.91
	Total	44	

Test Statistics^{a,b}

	Simplicity and Practicality	Clarity of methodology	Time and resource consumption	Quality and Usefulness of the results
Chi-Square	1.427	1.583	10.594	2.896
df	3	3	3	3
Asymp. Sig.	.699	.663	.014	.408

a. Kruskal Wallis Test

b. Grouping Variable: Features

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