

**DEVELOPING A CONSTRUCTION
MANAGEMENT SYSTEM BASED ON
LEAN CONSTRUCTION AND
BUILDING INFORMATION
MODELLING**

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The Author has published the following during the research, which share some of their contents with this thesis.

Refereed Journals:

Dave, B. & Koskela L. (2009) Collaborative Knowledge Management – A Construction Case Study. *Automation in Construction*. 18 (7), pp 894-902.

Sacks, R., Koskela, L., Dave, B. Owen, R.L. (2010). The interaction of Lean and BIM: a conceptual analysis. *Journal of Construction Engineering and Management*, Vol. 136, No. 9, September 1, 2010.

Koskela, L.J., and Dave, B. (2008). Process and IT. *Journal of Construction Innovation*. Vol 8, No 4, pp 224-249. (Editorial)

Book Chapters/Articles:

Maryland General Hospital Case Study – BIM Handbook 2nd edition, Eastman et al., Wiley Press. (2011) (Chapter 9, case study 9.4)

Conference Papers

Porwal, V., Dave B., Fernandez-Solis J., Koskela L. & Mehta H.S. (2012) State of Production Plan Reliability – A Case Study from India. *Proceedings of the 20th Annual Conference of the International Group for Lean Construction*, San Diego, USA

Pikas, E & Koskela, L & Sapountzis, S & Dave, B & Owen, R. (2011), Overview of Building Information Modelling in healthcare projects, in: 'Global health infrastructure - challenges for the next decade. Delivering innovation, demonstrating the benefits', HaCIRIC, Manchester, UK

Koskela, L., Owen, R.L., Dave, B. (2010). Lean Construction, Building Information Modelling and Sustainability. *Eracobuild Workshop*, Malmö, Sweden, April 14-16, 2010

Dave, B., Boddy, S., Koskela, L. (2010). Improving information flow within the production management system with web services. Proceedings of the 18th Annual Conference of the International Group for Lean Construction, Haifa, Israel.

Dave, B., Koskela, L.J., Kagioglou, M., Owen, R.L. (2009). Towards Business Process Improvement – A Construction Case Study. Proceedings of the 12th Europia Conference, Paris, France.

Dave, B., Koskela, L.J., Kagioglou, M., Bertelsen S. (2008). A Critical Look at Integrating People, Process and Information Systems within the Construction Sector. Proceedings of the 16th Annual Conference of the International Group for Lean Construction, Manchester, UK, pp 795-808

Dave B. & Goulding J.S. (2006). Collaborative Knowledge Management – A Case Study in Construction. INCITE World Conference of IT in Construction.

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To the memory of my grandmother

Abbreviations

2D	Two dimensional
3D	Three dimensional
4D	Four dimensional
5D	Five dimensional
ADM	Activity Definition Model
AEC	Architecture, Engineering, Construction
AIA	American Institute of Architects
API	Application Programming Interface
BIM	Building Information Modelling
BPR	Business Process Reengineering
CAD	Computer Aided Design
CAVT	Computer Aided Visualisation Tools
CCPM	Critical Chain Project Management
CEIS	Construction Enterprise Information Systems
CM	Construction Management
CPM	Critical Path Method
CVR	Cost Value Reconciliation
DB	Database
DSDM	Dynamic Systems Development Method
EOQ	Economic Order Quantity
EPC	Engineering, Procurement, Construction
ERP	Enterprise Resource Planning
GRN	Goods Receive Note
HTML	Hypertext Markup Language
HVAC	Heating Ventilation and Air conditioning
ICT	Information and Communication Technology
IT	Information Technology
KPI	Key Performance Indicator
LOB	Line of Balance

LPDS	Lean Project Delivery Process
LPS	Last Planner System™
MEP	Mechanical Electrical Plumbing
MIS	Management Information System
MIT	Massachusetts Institute of Technology
MS	Microsoft
OS	Operating System
PC	Personal Computer
PERT	Programme Evaluation and Review Technique
PMS	Project Management System
PPC	Percentage Plan Complete
QS	Quantity Surveyor
RFI	Request for Information
ROI	Return on Investment
TFV	Transformation Flow Value
UK	United Kingdom
VBA	Visual Basic Access
VDC	Virtual Design and Construction
VRML	Virtual Reality Markup Language
WPF	Windows Presentation Foundation
XML	Extensible Markup Language
XP	Extreme Programming

This research aims at improving construction management through simultaneous implementation of Lean Construction and Building Information Modelling. Specifically, the area of production management and control is addressed by developing a prototype software system that supports Lean Construction processes and provides a visual interface through Building Information Modelling.

The research addresses a practically relevant problem, and follows the Design Science Research method. The first stage of the research explores the problem area through the author's own observation of industrial practice, and also through a literature review. At the broad level, a two-fold problem is identified; first the problems with the production management process itself, and second the problems with visualisation and management of the product model and its integration with the production management. At the fundamental level, it is found that many of these problems are linked with the deficient theory behind production, which is predominantly based on the "Transformation" view of production. Additionally, it is found that the previous attempts at solving the problems of construction management through information systems have only met with limited success as they mostly address the peripheral processes rather than the core area of production management.

The second stage of the research explores and puts forward potential solutions to overcome the problems of production management. Lean Construction is identified as a partial solution to the production planning and control process. Specifically, the Last Planner System™ of production control is found to improve the productivity and efficiency of the production process by reducing variability, improving reliability and collaboration and introducing continuous improvement. At the same time, it is found that Building Information Modelling helps overcome many of the problems found with the traditional product management techniques (such as 2D and 3D CAD), by providing an object oriented, parametric and visual representation of the product. It is also found that the application of Building Information Modelling is relevant to all aspects of the construction process. Through a conceptual analysis, significant synergies between Lean Construction

and Building Information Modelling are identified, with applications also spanning the entire construction lifecycle. Specific benefits to the production management process are also found, backed by empirical evidence. However, it is also found that the current Building Information Modelling systems do not fully support an integrated implementation of production management. This particular aspect of an integrated and visual system, which would support the core production management process, is identified as a potential solution area.

The third stage of the research is dedicated to the design and development of a software system called VisiLean, which provides a collaborative planning and control platform, which is integrated with the Building Information Modelling platform, and which supports the production management process. A prototype system is developed through an iterative and incremental process, through simultaneous feedback, evaluation and review.

The fourth stage of the research includes the evaluation of the VisiLean prototype through a demonstration and feedback process. At this stage, the design, development and evaluation process is analyzed and discussed. Finally, the contributions to the theory and the body of knowledge are identified, along with the suggestions for future development.

1 Introduction

1.1 Background

The problems faced by the construction industry are well known both internationally and in the UK. Some of the most criticised issues within the industry are:

- **Inefficient (wasteful) processes:** The construction process is highly inefficient. In terms of productivity, a meta-analysis of wasted time in construction was conducted by Horman and Kenley (2005), where the authors reported that over the last 30 years, almost 49.6% of time was wasted during construction in non-value adding activities. Similarly, a research carried out in Sweden showed that only 15-20 % of the workers time is spent in direct work (i.e. carrying out the planned activity) (Jongeling & Olofsson 2007). There are similar studies around the world, which have reported sub-optimal performance of construction projects in terms of productivity and efficiency (Teicholz et al., 2001, Ramaswamy and Kalindi, 2009). A separate study in USA in the productivity of non-agricultural industries has found that the construction industry has actually seen a decline in productivity over recent years (Teicholz et al., 2001).
- **Cost/time overruns:** Seldom does a construction project finish within time and budget (Ahmed, et al., 2003; Chan and Kumaraswamy, 1996). This results in penalties to contractors and on many occasions, lengthy legal disputes within the supply chain as everyone tries to find a way to recover losses and someone to blame.
- **Fragmentation:** Fragmentation is a factor that contributes to some of the problems listed above. Due to the risk aversion strategies of the construction firms, they are now merely planning and management companies who employ large number of specialised subcontractors on a typical construction project. This combined with other supply chain members such as architects, engineers and material suppliers; it makes it a highly fragmented and complicated industry (Harvey, 2000).

- **Technological aversion:** Construction is also seen as an industry, which lags behind other industries such as manufacturing in terms of technological adaptation. In general, there has been an active effort by the industry in recent years to implement technological solutions to improve the process, but due to misguided efforts, the results have not been satisfactory (Koskela, and Kazi 2003; Tatari et al., 2006).

It is equally important to understand the critical success factors, as it is to understand the root causes of failure on construction projects. Zhang (2005) reports on a survey carried out with construction managers to identify success factors behind desirable outcomes on construction projects. The top five factors outlined are:

1. Planning & control
2. Communication/coordination
3. Labour availability and quality
4. Equipment and tools (availability)
5. Working methods.

The first two factors mentioned above are significant as they govern the overall construction process and also affect the next three success factors up to a degree. This is due to a culmination of several factors that have weakened the production management processes. In a study of the main root causes of failure behind construction activities, Koch (2005) reports production planning and control, communications and cooperation, and design activities as the main factors contributing to problems. In construction, the traditional planning and control processes and also the communication/coordination between stakeholders have been problematic (Sacks et al., 2010a; Navon and Sacks, 2007; Sarhan and Fox, 2012).

Looking specifically at the problems in the UK, compared to the global industry, there are both overlapping and specific problems. The problems faced by the construction industry in the UK are also raised in several high profile reports that have been published over the years, which highlight the inefficiencies with the construction industry. These include reports such as Constructing the Team

(Latham, 1994), Rethinking Construction (Egan, 1998) and Accelerating Change (Egan, 2002), which have highlighted key issues faced by the industry namely, the fragmentation, low and unpredictable profitability, low investment in innovation, and focus on cost rather than quality which all contribute up to a degree to failure.

Latham's report was the initial catalyst in starting the change process for construction industry. The report focussed mainly on collaboration within the team stating that up to 30% savings could be achieved in five years. In Rethinking Construction (Egan, 1998), which focussed strongly on processes and collaboration, five key drivers for change were identified.

1. Committed leadership
2. Focus on the customer
3. Product team integration
4. Quality driven agenda
5. Commitment to people

The report also identified four process improvement proposals:

1. Product development
2. Partnering in the supply chain
3. Project implementation &
4. Production of components (offsite)

The Egan report also recommended implementation of Lean principles to improve process efficiency of the construction process. There has been a drive to implement Lean Construction in the UK due to the significant emphasis placed on implementation of lean principles in the construction industry, ever since the publication of these reports. This has been reflected in several training and implementation programmes such as the Construction Lean Improvement Programme (CLIP) that has been offered by the Buildings Research Establishment (BRE) since 2003, and recently the BuildLean guide (Terry and Smith, 2011) by Construction Industry Research and Information Association (CIRIA). Also, to help disseminate lean construction practices in the UK, a non-profit organisation Lean Construction Institute (UK), has been established.

The Accelerating Change (2002) report also highlighted problems with the construction supply chain and recommended that the industry should aim to take measures to improve the collaboration within the supply chain. It set the target of 20% of projects to be undertaken by integrated teams by 2004 and 50% by 2007.

However, even though the above mentioned reports have been able to kick start an improvement process across the industry, and several organisations such as the aforementioned Lean Construction Institute (UK) have been established, the uptake of lean construction in the UK has been quite slow and the industry has not met the targets by a considerable margin as reported by the recently published report “Never Waste a Good Crisis” (Wolstenholme et al., 2009). In the report, results from an extensive online survey were published, which was completed by nearly 1000 professional people from the industry. The survey gathered opinions across the industry about progress made since the Egan report and also put industry performance data in context to highlight key issues prevailing in the industry. Figure 1. Perception of main benefits of the Rethinking Construction agenda (Wolstenholme, 2009) demonstrates the perception of the industry of the benefits that have been brought by the Rethinking Construction agenda.

The general perception that emerged from the survey was that while there are pockets of excellence, the majority of the industry hasn’t changed significantly. Also the KPIs (Key Performance Indicators) monitored since last 10 years confirm the findings as demonstrated by Figure 2. Industry performance since 1999 (Wolstenholme, 2009) Here it can be clearly seen that the “time saving” target set by Egan (as shown by pale blue line) is only partially met by selected demonstration projects (as shown by light blue bars), whereas the industry average remain relatively unaffected (dark blue bars).

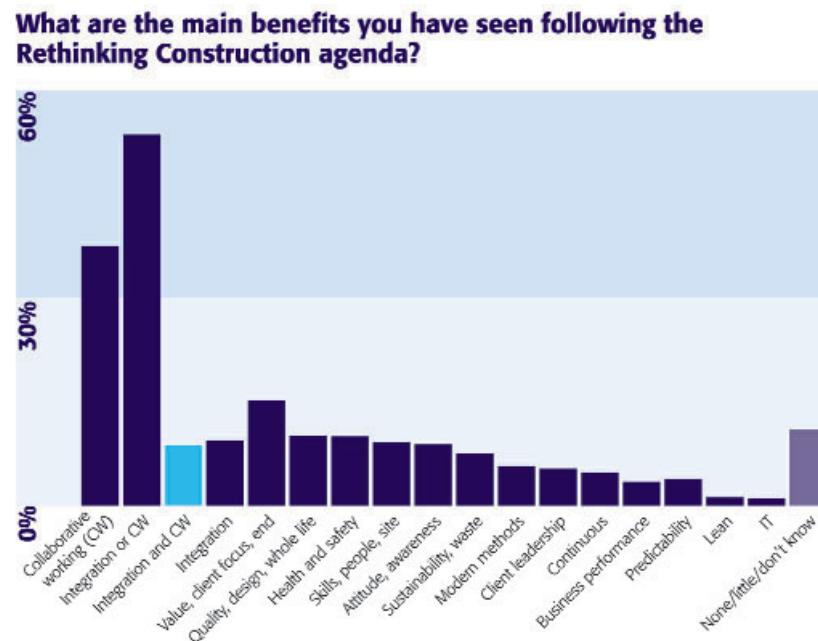


Figure 1. Perception of main benefits of the Rethinking Construction agenda (Wolstenholme, 2009).

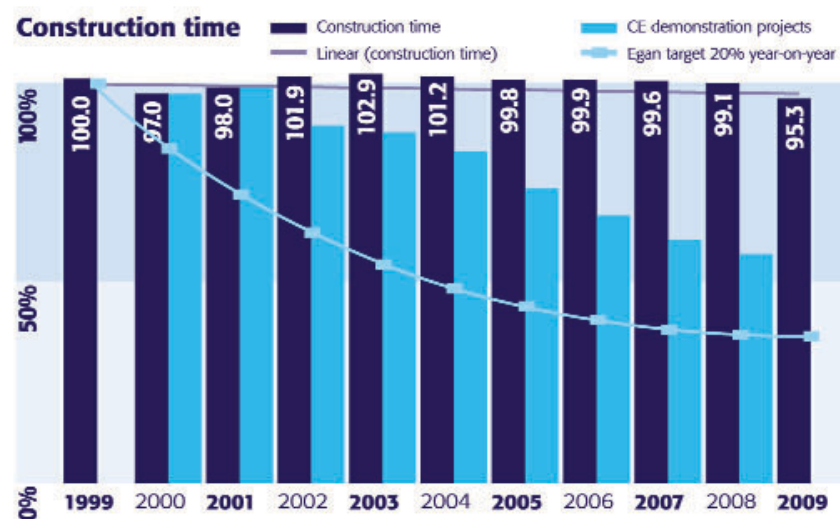


Figure 2. Industry performance since 1999 (Wolstenholme, 2009).

The report claims that the stated aim of genuinely changing the nature of the construction industry has not been met and that there is not enough evidence of a genuine intent to change across the construction industry to achieve the targets set by Egan's vision of the modern construction industry.

There are several suggestions made by these reports as noted above, however, one of the common suggestions across all reports is that of the need to improve

process efficiency and collaboration between the supply chain members through the application of lean construction.

Although there are many tools and techniques associated with Lean Construction, one of the most implemented and effective tools in Lean Construction implementation is The Last Planner System™ (Ballard, 2000). The Last Planner System™ emphasises the need to take into consideration information and resource constraints while preparing detailed near term and short-term plans. Also, as the name suggests, the Last Planner System™ emphasises the involvement of the construction teams including foremen, site supervisors and project manager(s) while planning in a collaborative way. The Last Planner System™ along with other lean construction tools rest their foundation on the TFV (Transformation, Flow and Value) theory of production developed by Koskela (2000). In TFV, there is a greater emphasis on managing the flow aspect of production while taking care of the actual transformation process, which should ultimately lead to value generation for the client. The Last Planner System™ takes care of the flow aspect by the process of constraints analysis, where individual constraints are analysed and managed for each task. This detailed planning workflow demands accurate and timely information, especially from constraints (resource) management perspective.

1.2 Justification for Research and the Research Problem

This research aims to solve a problem that is practically relevant and also has potential for theoretical contribution, that of inefficient production management systems in construction. The research is relevant in the real world and makes contributions to the production management theory in construction.

As discussed above, lean construction has been identified as one of the potential process improvement techniques to overcome the challenges faced by the construction industry. However, as noted above, the performance of the construction industry has not improved a great deal even after the recommendation of lean construction techniques. This view is also supported by a number of studies that have been carried out to identify barriers to the effective implementation of lean construction in the industry, which have highlighted the

use of inappropriate tools as one key factor (Johansen et al., 2002, Bashir et al., 2010, Sarhan and Fox, 2012). Furthermore, Sarhan and Fox (2012) identified “Lack of Process Based Project Management Systems” as one of the significant barriers to the successful implementation of Lean Construction in the UK. Hence it emerges that while lean production management is one of the recommended approaches to improve the efficiency of the construction process, the tools and systems that support it are not yet fully developed.

The importance of information management from lean construction perspective, with greater emphasis on managing flow has also been highlighted by several authors (Sacks et al., 2010a; Sriprasert and Dawood, 2003; Navon and Sacks, 2007; Dave et al., 2010). Chua et al. (2003) emphasise the role of information technology in planning, especially from constraints management perspective, however they conclude that the current information management systems do not offer effective solutions. During a survey of a large-scale project management information and control system, Fitcher (2001) highlighted the need for the data entry at the project level as one of the most significant obstacles to the successful implementation. Similarly Koskela and Kazi (2003) have brought to attention the ineffectiveness of construction information systems as they do not support the core production processes, and in many cases prove to be counterproductive.

From a theoretical perspective, the effects of TFM on production management in construction have been very well explored (Koskela 2000), however its effects on enabling systems such as information management are not yet tackled (Dave et al., 2008). Analysis of the effects of TFM theory in information management systems could help identify and potentially resolve the problem of its ineffectiveness in production management.

Thus, there is a two-fold research problem that is being addressed. Firstly, the problem with the production management process is considered, and subsequently the problem with the inefficient information management systems that support the production management process is addressed.

1.3 Research aim and objectives

Research Aim: This research aims at improved construction management through lean construction principles and building information modelling. To realise this aim the following research objectives have been identified.

Research Objectives:

1. To identify and analyse the main deficiencies within the current construction management process
2. To explore the solution area and develop a conceptual framework of processes and tools for a production management and control system for construction
3. To design and develop a prototype of a computer based system based on the above framework.
4. To evaluate the solution and analyse/synthesise the results

1.4 Research method

The type of method(s) used in research depends on the type and nature of research being conducted. In this case the research being carried out falls within the disciplines of information science and construction management as the aim is to develop a computer based system to support production management in construction.

Lukka (2003) describes the constructive research approach as a research procedure for producing innovative constructions, intended to solve problems faced in the real world and, by that means, to make a contribution to the theory of the discipline in which it is applied. It is suggested that all human artefacts such as models, diagrams, plans, and information systems and their designs are constructions. The core features of the constructive research approach require that it (Lukka, 2003):

- Focuses on real-world problems felt relevant to be solved in practice
- Produces an innovative construction meant to solve the initial real-world problem

- Includes an attempt for implementing the developed construction and thereby a test for its practical applicability
- Implies a very close involvement and co-operation between the researcher and practitioners in a team-like manner
- Is explicitly linked to prior theoretical knowledge, and
- Pays particular attention to reflecting the empirical findings back the theory

A detailed methodology Chapter (Chapter 2) discusses the methodology used and the justification behind it in more detail. It also explains in detail the steps taken to develop and evaluate the solution. Here, it should be noted that both design science and constructive research approaches are similar in nature and both provide guidelines outlining steps to be followed while designing a solution. Chapter 2 covers both, Design Science (Hevner et al., 2004) and Constructive Research (Lukka, 2003) approaches and puts forward a set of guidelines (research framework) that were developed specifically for this research.

1.5 Scope

This research is limited to the production management and control on site on a construction project. Specifically the planning scheduling workflow to support the Last Planner System™ is targeted. The research aims to develop an information system to improve the production management process, however, the actual programming and database development are not within the scope of this research, but taken care of by a fellow researcher. Particular limitations related to this aspect are described in relevant Chapters in detail.

Also, the research takes into consideration the product and process integration aspect while designing a solution. Here it is assumed that a product model (Building Information Model) already exists and is made available to the production team. The research does not make any suggestions or recommendations regarding the design practice.

However, it should be noted that the domain of production management and control also encompasses design aspects (i.e. design can be treated as a part of the production system, and also that design tasks have to be managed just like construction tasks), and thus potential solutions in the form of Lean and BIM can

be applicable to the whole process of design and construction (and operations). From this perspective, exploration of design management workflow, i.e. managing design production (planning and controlling of design tasks using the Last Planner™ process) emerges as one of the possible areas that the research can address. Nevertheless, due to the limitation of time and resources it is not possible to explore all these areas within one doctoral thesis. Due to the background of the research candidate and the problem area being tackled, the research only focuses on the construction management aspects of the production process, predominantly on site based processes (in alignment to the use of the Last Planner™ process to site based construction).

Finally, as the research mostly took place in the UK, the construction processes and other choices related to the geographical context were related to this region. However, during the initial design (requirements capture) and then at the evaluations stage, several overseas organisations provided their feedback, most of them belonging to the lean community.

1.6 Contents

The remaining part of this document is divided in six Chapters. The second Chapter describes the research methodology selected and the justification behind its selection. It also outlines the specific research method that was followed while designing a solution.

The third Chapter begins by exploring the problem area of production management and information systems in construction through observations from industrial practice. These observations are from researcher's own experience while working with these organisations. Subsequently, the Chapter explores the problems with the production management and information systems from literature review.

The fourth Chapter explores the solution area in depth. Here the solution area being Lean Construction and Building Information Modelling. This Chapter is divided in two main parts, first the theoretical foundations of lean and BIM are studied, and secondly the prior research in addressing the area of production management with lean and BIM are explained.

The fifth Chapter is also divided in two main parts; the first part discusses the design of the solution, which is called VisiLean, while the second part details the development process and the iterations of the prototype. This is followed by the evaluation of the prototype through demonstrations, discussions and a pilot project, and analysis of the evaluations in the sixth Chapter.

Finally, the conclusion and discussion Chapter provides a synthesis of the research, main conclusions, contributions to theory and areas of future research.

2 Research Methodology

It is important to select an appropriate research method suitable for the problem at hand. As mentioned in previous chapter, the research problem falls within the realm of production management in construction and Information Science, and is practice oriented in nature. Design Science is fundamentally a problem solving paradigm (Hevner, 2004), which has its roots in engineering and the science of the artificial (Simon, 1996). It is suggested by Lukka (2003) that all human artefacts such as models, diagrams, plans, and information system designs are constructions. Design Science is increasingly being applied in the realm of information science research, but it is also being applied to other sectors including construction management (Tezel, 2011; Rooke, 2012). The core features of the constructive research approach require that it (Lukka, 2003):

- Focuses on real-world problems felt relevant to be solved in practice
- Produces an innovative construction meant to solve the initial real-world problem
- Includes an attempt for implementing the developed construction and thereby a test for its practical applicability
- Implies a very close involvement and co-operation between the researcher and practitioners in a team-like manner
- Is explicitly linked to prior theoretical knowledge
- Pays particular attention to reflecting the empirical findings back the theory.

This chapter provides details on the selected research method, starting with need and justification followed by a comparison between Design Science and Constructive Research. Following this, a comparison between Design Science and Natural Science, and place of Constructivism in Information Science is provided. This is followed by research process followed by VisiLean including the overarching research framework, research output and evaluation.

2.1 Need and justification for Constructive Research

Both Constructive and Design Science research deals with “real world” practical problems as well as considering its theoretical contributions; it links the research

and academic world with the industrial issues (Lukka, 2003; Hevner, 2004). Hence, the relevance of topic (in other words quality of research problem) improves significantly when using constructive research methodology in certain research fields.

In research areas dealing with practical problems or issues that are close to the industry, using other research methods exclusively (i.e. surveys, observation, interviews) leads to unsatisfactory and low results. This is due to increasing frustration of organisations being asked to participate in surveys or interviews, as they feel that they don't get much in return for their effort (Lukka, 2003). Instead, in constructive research, emphasis is on two-way communication as the researcher works very closely with organisations imparting valuable knowledge in the process.

Lukka (2003) also mentions that to validate the research, and identify whether a certain solution/hypothesis/framework really works, is to actually test the idea in the field with practitioners. It is extremely difficult to validate such research just by asking questions or distributing questionnaires or collecting data through surveys. The constructive approach advocates the practice of testing the "truth" by finding out what works in practice through direct intervention of the researcher(s).

Figure 3 illustrates the key elements of the constructive research approach (Lukka, 2003).

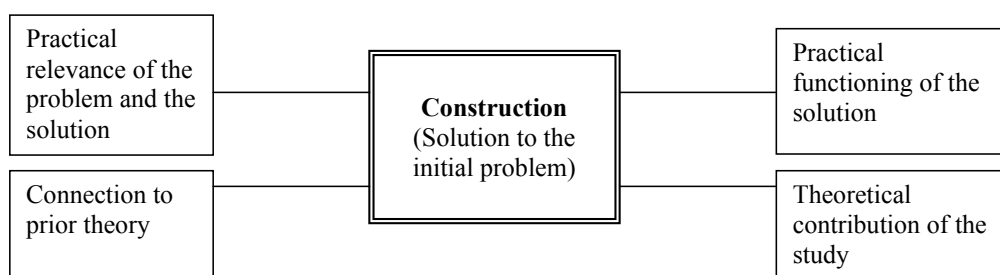


Figure 3. Elements of constructive research (Lukka, 2003).

Research scholars in management and information science argue that whilst rigorous research is paramount to create new knowledge, it should also deliver application and relevant results for practical use (Holmström et al., 2009; van Aken

2004). This demand has earlier been satisfied through the development of action research approach, and later through the use of constructive research approach and Design Science research approach (Piirainen and Gonzalez, 2013). Both, Constructive Research Approach and Design Science aim to increase the relevance of management and information science research by putting the theory to practice through designing and/or constructing “constructions” (Kasanen et al., 1993).

According to Hevner et al. (2004), two paradigms characterise majority of the research in Information Systems, that of behavioural science and design science. Whereas the behaviour science view develops or verifies theories that explain or predict human or organisational behaviour, design science paradigm extends the human/organisational boundaries of understanding by creating new and innovative artefacts. In information science the importance of design is emphasised and researchers have argued that the realm of information science research is directly related to design (Glass, 1999; Winograd, 1997).

Hevner (2004) explains that unlike behaviour science research, which seeks to predict or explain phenomena that occur with respect to artefact’s use, design science creates and evaluates Information Technology artefacts intended to solve identified organisational problems.

Hevner et al. (2004) also define a design process as a “sequence of expert activities that produces an innovative product (i.e. the design artefact). The authors also explain the dichotomy of design science paradigm, as design is considered both as a process and a product. The process is explained as a sequence of expert activities through which an innovative product (i.e. the design artefact) is produced. Subsequently, the evaluation of the artefact provides a better understanding of the problem (and a solution) in order to improve the quality of both the design process and the designed artefact. This activity of building an artefact and evaluation is carried out in a loop a number of times before the final artefact is generated. From the perspective of this research, this particular aspect of having an iteration cycle between artefact design and evaluation can be considered significant and has a potential to play a central role in the research.

Hevner et al. (2004) provide a framework for Information Science research based on the design science method. Table 1 (Research Process followed for VisiLean) is based on this framework and explains each step taken in the research in the context of this framework.

2.2 Comparing Design Science with other approaches

It is important to understand the position of Design Science with other research methods. Also, as Constructive Research and Design Science research are arguably similar, it is important to understand the key differences and converging aspects of these two methods. This section begins with comparing design science with constructive research and then compares design science with natural sciences. Finally, it describes the position of constructivism in Information Science research to provide clarity on the selection of research method.

2.2.1 Convergence of design science and constructive research

In the literature, two approaches are found, which are argued to refer to a type of research that emphasizes the creation of something new into the world: constructive research and design science research. The question of the relation of these approaches arises. Piirainen and Gonzalez (2013) provide a detailed and critical comparison between Design Science and Constructive Research approaches. The authors state that from a definition perspective, one of the main differences is that when Design Science literature puts more weight in applying previous knowledge through a specific theory in the design, Constructive Research proposes a softer or creative approach (however, Constructive Research does not reject the use of a theory based approach). Piirainen and Gonzalez (2013) provide a further explanation through simplification of the general definition of Design Science research. In Design science, the basic logic of discovery is of a deductive nature, where a researcher applies a kernel theory to a previously unsolved problem (in order to solve it). By following this method, the theory provides general principles that can be applied to the specific problem and, in doing so, contributes to the theory by providing solutions based on it, or by extending the problem domain and generalisability of design principles. Whereas, in Constructive Research, the solution is based on deep knowledge of the problem and application of existing theory through a heuristic process.

On the outset, there are many similarities between the two approaches, with only slight differences in terminology. For example, where Constructive Research uses the word “construction” Design Science uses the word “artefact”, but the definition and use of these terms in both approaches are quite similar. From process perspective too, both approaches have similarities. For example, both processes go from developing problem awareness and definition to solution proposition, artefact development and evaluation. In terms of application context, Design Science method seems to be applied predominantly in Information Science disciplines, but also some examples in Knowledge Management and management science exist (Markus et al., 2002; Osterwalder, 2004, Wu, 2009), whereas Constructive Research has a more generic approach and is being applied to both Information Science and general management applications (Kasanen et al., 1993; Hilmola, 2007).

In summary, it emerges that there are more similarities between these approaches than there are differences, and it is possible to frame the research within the framework of either of these approaches while taking guidance from both simultaneously.

2.2.2 Comparison of Constructive Research with Natural Science

March and Smith (1995) compare natural science research with information science research (study of the artificial), where natural science includes research in physical, biological, social and behavioural domains, information science (or technology) research deals with human creations such as organisational and information systems. According to the authors, natural scientists develop sets of concepts or specialised language with which they characterise phenomena. These concepts are then used in higher order constructions such as laws, models and theories, which make claims about the nature of reality. On the other hand, design scientists work towards creating models, methods and implementations, which are innovative and valuable.

March and Smith (1995) go further in differentiating natural science with design science. The authors mention that although design science produces artefacts and artificial phenomena, natural science can address both natural and artificial

phenomena. As an example, natural scientists can try to understand organisational processes or implications of an information system implementation on collaboration between employees. Hence the distinction is not made on the topic being studied alone, but is based on the research objectives. Whereas natural science aims to understand phenomena, design science aims at developing ways to achieve human goals. Once constructed, design science artefacts could become the subject of natural science research, for example by studying their effect on behaviour of employees within an organisation.

Hevner et al. (2004) shed further light on the subject of positioning design science against natural science. The authors claim that whereas in natural science, the underlying assumption is that somewhere some “truth” exists and somehow it can be extracted, explicated and codified. Hence, the behaviour or natural science paradigm seeks to find “what is true”, where on the other hand the design science paradigm seeks to create “what is effective”. The authors also go further and mention that the design science method is proactive while dealing with technology, as it strives to create innovative artefacts to solve practical information system related problems. On the other hand, the behaviour-science research methods are reactive with respect to technology, as it takes it as a “given” and attempts to study and explain the acquisition, implementation, management and use of such technologies.

In critical analysis, according to Hevner et al. (2004), the risk in design science is to create artefacts that although well designed, are not grounded in any theory and hence useless in practice. Similarly, the risk in behaviour-science research is the overemphasis on theories and failure to take into account capabilities of innovative and state-of-the art technologies, resulting in development of theories or principles that address out-dated technologies.

2.2.3 Position of Constructivism or Interpretive Philosophy in Information Science Research

When providing a comparison between different approaches to Information Science Research and their relation with the Design Science approach, Hevner et al. (2004) and March and Smith (1995) position behavioural science as a branch of

natural science. It is important to pinpoint that there is a branch of behavioural science that does not fall into natural science, namely the constructivist approach. For the sake of clarity, it is necessary to state that this constructivist approach is completely different from constructive/design science research, although it (as other approaches in behavioural science) can be used in a number of stages of a design science research cycle, especially in creating awareness of the problem and in evaluation.

Mallon (2013) explains social constructionist claims as having the form of a two part relation: X socially constructs Y. Orlikowski and Baroudi (1991) describe that in interpretivism, reality and our own knowledge of reality are not independent of the social actors (i.e. us, humans and society in general), but are perceived as a social construction or interpretation. Hence, the world is not perceived as constituting of fixed objects, but rather as an “emergent social process, and as an extension of human consciousness and subjective experience” (Burrell and Morgan, 1979). Hence, the aim of interpretivism or constructivism is to understand how social actors belonging to a particular group interpret their reality and associate it with meaning, and to demonstrate how these meanings, beliefs or intentions lead to form their social action (Orlikowski and Baroudi, 1991).

Within this context, the use of constructivism is especially useful when trying to explore underlying connections among different parts of social systems, such as a user group, organisations etc. For example, studies into how a particular technology is perceived by a group of users or how the adoption of a certain technology has occurred within a certain organisation are potential topics of research under the constructivism approach.

2.3 Process of constructive research

March & Smith (1995) provide an elementary framework as shown in Figure 4 for conducting constructive research. This research matrix provides sixteen cells containing potential research efforts. The research could lie in one or more cells depending on the context, where each cell could have different objectives and use different methods to satisfy them. Research can build, evaluate, theorise or justify theories about constructs, models, methods or instantiations.

		Research Activities			
		Build	Evaluate	Theorize	Justify
Research Outputs	Constructs				
	Model				
	Method				
	Instantiation				

Figure 4. A research framework for design science research (March and Smith, 1995).

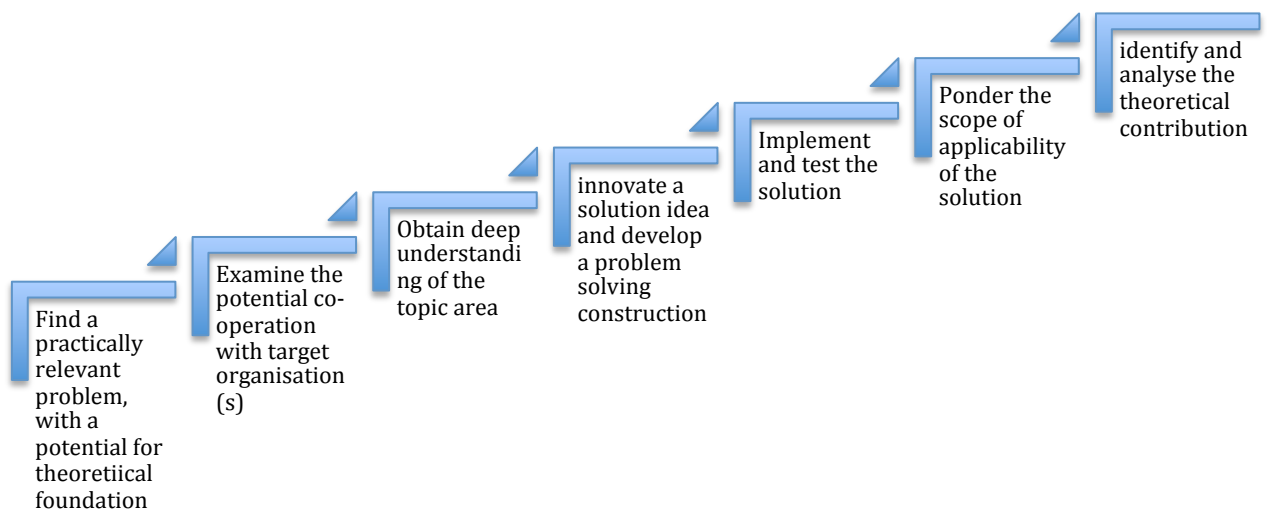


Figure 5. Steps taken in design science research (Lukka, 2003).

Lukka (2003) provides a set of steps as shown in Figure 5 to characterise typical research process followed by constructive research. These steps are described based on Lukka (2003).

2.3.1 Find a practically relevant problem, which also has potential for theoretical contribution.

In most cases the problem is selected through researcher's personal experience in the field, i.e. it is observed/experienced first-hand. Additionally, discussing with practitioners and experts is another approach to identify practical problems. If identifying a problem through literature search or other means, a close observation of the problems faced by the industry through industry journals and other such means can also be quite useful. Essentially, the problem area should have both – practical and theoretical concerns.

2.3.2 Examine the potential for long-term research cooperation with the target organisation.

As constructive research deals with a practical problem, it is essential that the researcher(s) has access to a target organisation (or several if relevant) through the duration of the research. In majority of the cases input from both sides will be required at certain stages and this should be made explicit at the beginning of the research. Also, the credibility of the researcher and research topic and contribution made by it to the organisation should be established in the target organisation(s) to create trust. Not always necessary, but a formal research agreement outlining the research activities/schedule, key milestones, funding and access to information can be developed at the beginning of the project.

2.3.3 Obtain deep understanding of the topic area both theoretically and practically.

In this step, the researcher starts by getting a better understanding the organisation's practices using usual ethnographic methods such as direct observation, interviews and desk study in order to gain deep understanding of the problem area. Also, it is expected that the researcher should be well informed about the existing practices and theories prevailing in the problem domain so that towards the later part of the research he/she can analyse the outcome and its contribution to the existing theories and research domain. The overall achievement of this step is to outline the problem and existing situation in detail before setting out to find potential solution.

2.3.4 Innovate a solution idea and develop a problem solving construction, which also has potential for theoretical contribution.

This is the one of the core parts of the research being conducted. Here, the researcher develops a conceptual solution to tackle a problem he/she identified in the first step, keeping in mind the surrounding issues identified in subsequent steps and also ensuring fit within target organisation(s). In this step the researcher identifies whether a solution can be developed in the first place, if not feasible, either the research is dropped or significantly changed. Also, as this phase is highly creative in nature it is difficult to follow a particular research method. Most solutions are developed in an iterative (trial and error) fashion and several loops of implementation and analysis are also carried out. The process of identifying the solution can also be quite valuable contribution to knowledge regardless of the end result.

2.3.5 Implement the solution and test how it works

The solution developed in the previous step is now implemented in a practical environment in the chosen organisation. This is where the solution gets tested not only from the technical perspective but also from the process perspective, wherein the processes needed to run the solution are also tested. Throughout the implementation, the researcher has to actively take part in the process as he/she is the one who is most familiar with the concept. This step differentiates the design science research from traditional research methods where hardly any empirical evidence of the innovative construct is gathered, or the participation of the researcher in any such process is limited.

2.3.6 Ponder the scope of applicability of the solution

This is the analysis step where the researcher along with the target organisations start analysing the outcome of the implementation carried out in the previous step. Regardless of the outcome (whether successful or not), there will be a scope to learn from the implementation process. If successful, the further diffusion of the solution in the wider industry should also be considered along with the process steps. This should also form the part of the contribution of knowledge.

2.3.7 Identify and analyse the theoretical foundation

From a research and academic perspective, this is the most important part of the research. Here, the researcher analyses the findings and identifies the implications for the original theory(ies). Lukka (2003) identifies two distinct type of contributions to the theory, namely the novel construction itself and the positive relationships behind the construction. In the first instance, if the innovative solution is found to be successful, then that itself provides a contribution to the theory/prior literature. Secondly, the application of the existing theory/prior literature while construction the innovative solution, and its relationship with the solution and outcome is also of importance. Theory refinement is the most important part of the research project, where our prior beliefs on the means-ends relationships are reevaluated.

2.4 Research outputs

Figure 4 demonstrated a research framework showing the relation between research outputs and research activities. The following describes the research outputs that were generated through the constructive research process in form of constructs, model, method and instantiation. Figure 6 shows the framework for research, which is based on the discussion above and the framework suggested in Figure 4. It should be noted that while “Justification” is also a part of the constructive research framework as shown in Figure 4, it is outside the scope of this research. The justification activity as explained by March and Smith (1995) is aimed to gather evidence to test the theory, which the research is building or contributing to. However, due to the limited time available to carry out the research, it has not been possible to gather evidence to test the theory.

2.4.1 Constructs

Initially, the Lean and BIM conceptual framework (Sacks et al., 2010), which is described in detail in Chapter 4, served as the overarching conceptual framework behind the research and provided a background to the research. This Lean and BIM framework was developed to identify the conceptual synergies between Lean Construction and Building Information Modelling where a matrix between main lean principles (16) and leading BIM functions (8) was developed. The framework and the overarching research identified significant synergies between these two

areas. The author was one of the main contributors to this framework (as one of the co-authors).

2.4.2 Model

Subsequently, a system specification and functional requirement specification for a potential lean and BIM system as described will be developed. This will serve as the model and as described below, will populate both build and evaluate cells. VisiLean development itself will act as the evaluation part of the model and subsequently the model will be evaluated when VisiLean will be trialled on a construction project.

2.4.3 Method

Once the model has been developed, a method of development and also a method of implementation will be chosen. The latter here is of much higher importance, as the method of implementation of such a system has the potential to guide future implementations of similar systems across the industry if evaluated, analysed and theorised correctly.

2.4.4 Instantiation

Instantiation in form of VisiLean prototype will take place in the build phase. Once the prototype is built, it will be evaluated in several stages, first through a series of workshops and discussions with the collaborating industrial partners and then through implementing on an on-going construction project. Feedback gathering through interviews and workshops with key personnel, and direct observation will be used to evaluate the system.

		Research Activities		
		Build	Evaluate	Theorize
Research Outputs	Constructs	Lean and BIM Conceptual Framework		Lean and BIM Conceptual Framework
	Model	Lean and BIM Conceptual Framework, VisiLean Architecture	Lean and BIM Conceptual Framework, VisiLean Architecture	VisiLean Architecture
	Method	Implementation process	Implementation process	
	Instantiation	VisiLean Prototype	VisiLean Prototype, Trials	VisiLean Prototype

Figure 6. Research Matrix for VisiLean (adapted from March and Smith, 1995).

2.5 Research Process for VisiLean

Based on the discussion above and the process outlined in Figure 5, a research process as described in Table 1 below was developed.

Table 1. Research Process followed for VisiLean.

Stage	Description	Corresponding features in research realisation
1	Find a practically relevant problem, which also has potential for theoretical contribution	Through direct observation and subsequently through on-going discussion with industry partners the problem will be identified. A two-stage problem – first, the information systems supporting the lean production process are inefficient, secondly the systems supporting the product representation (building information model) do not integrate well with the project management systems (especially from lean management perspective).
2	Examine the potential for long-term research cooperation with target organisation(s)	Industry partners including software development companies in the area of construction management and BIM and large construction organisations who are at the forefront of lean and BIM implementation collaborated during research. No formal agreements have been signed, however, the cooperation has been excellent and access to information and availability of resources to support the research has been continuous.

Stage	Description	Corresponding features in research realisation
3	Obtain deep understanding of the topic area both practically and theoretically	Several methods have been used. Literature review, case studies, interviews, site visits formed the initial part of this stage while building the research problem and understanding current situation. Secondly, through workshops, and interviews practical understanding of the problem was gained that subsequently led to the next step of designing the solution.
4	Innovate a solution idea and develop a problem solving construction, which also has potential for theoretical contribution	Initially a conceptual framework and broad information system architecture based on the requirements capture during workshops was developed. Subsequently functional specifications and a prototype was developed and demonstrated through meetings and workshops.
5	Implement the solution and test how it works	Workshops and site visits to demonstrate the prototype to target users have been carried out. Based on the feedback received the system has been modified to suit new requirements. A pilot project has also been carried out and feedback received.
6	Ponder the scope of applicability of the solution	Initial feedback during the pilot implementation and demonstrations have been analysed. However, further analysis and wider applicability is outside the scope of this research.
7	Identify and analyse the theoretical contribution	Essentially, the theoretical contribution will be to both – information systems within construction and the construction management theory (TFV).

2.6 Evaluation of research

March and Smith (1995) describe the evaluation process as “we evaluate artefacts to determine if we have made any progress. The main question is how well does the newly constructed artefact work?” Lukka (2003) mentions that this is the first practical test (“market test”) of the designed construction (artefact) and should be viewed as one of the key characteristics of the constructive approach, relying on the pragmatic notion of truth. Lukka (2003) also mentions the importance of the deep involvement of the researcher with the practical implementation itself, and that he/she (researcher) should actively sell the innovative idea to target organisations, consider training of key personnel and consider pilot tests to thoroughly evaluate the concept.

Hevner et al. (2004) emphasise that the utility, quality and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.

Evaluation according to Hevner et al. (2004) is a crucial component of the design science research process where the business environment establishes the requirements upon which the evaluation of the artefact should be based. The authors note that the environment includes the technical infrastructure which itself is incrementally built by the implementation of new information technology artefacts. Hence the process of integrating the artefact within the technical infrastructure of the business environment is itself part of the evaluation of process.

Although the overarching research framework adopted is Design Science/Constructive Research, principles for qualitative research are used to collect feedback from the industry (both during problem analysis and evaluation stage). This is as feedback gathering through interviews and workshops fall within the realm of qualitative research. Hence, guiding principles from the qualitative research domain are applied in conducting interviews and selecting the sample size.

According to Mason (2010), sample sizes in qualitative studies are normally much smaller than those in quantitative studies. Ritchie et al. (2003) have provided a number of reasons for this. One of the main reasons is that with qualitative studies, which use techniques such as interviews, larger sample size does not necessarily lead to more information (Guest et al., 2006). This is because a single occurrence of a code (a term used for a piece of information in qualitative research) is all that is needed to include it in the analysis framework. Whereas frequencies (number of occurrences of a code) are highly important in quantitative research, they are rarely important in qualitative research (Crouch and Mckenzie, 2006). This is also because context and meaning have higher importance in qualitative research than making/confirming generalised hypothetical statements (Mason, 2010).

However, as it is possible to have a wide range of opinions from a set of participants, the qualitative research sample size should be large enough so that it covers the whole range of input. Although it is not possible to exactly determine the sample size before the study begins, it is possible to apply the principle of “saturation”. Saturation in qualitative studies can be defined as a point where the

collection of new data does not shed any new light on the issue being investigated (Glaser and Strauss, 1967).

A relevant principle here is that of Consensus Theory, where Romney et al. (1986) propose that experts tend to agree more with each other (within the context area of their expertise) than novices. The authors provide a mathematical proof of their theory and confirm that small samples, for example as small as four individuals, can render extremely accurate information with a high confidence level (within the research domain). Although Consensus Theory was originally intended for and deals with knowledge instead of experiences and perception, it is still relevant to open ended questions, which deal with perception and beliefs.

Further details of the evaluation process, methods followed and the results obtained through evaluation are described in Chapter 5 and 6.

2.7 Summary of Research Methodology

This research deals with two separate disciplines, namely production management and information science, where the aim is to develop an information system that solves a practical problem within the area of production management. Due to the nature of the problem and solution being developed, the research falls within the boundaries of design science. In this chapter, the benefits of applying Design Science method to practical and industry related problems are highlighted against other methods. Especially, as the Design Science method provides a flexible yet rigorous and structured method to develop a solution that is relevant to industry, it is found to be most appropriate for this research. It is also found that there are more similarities than differences between constructive research and Design Management, and for sake of simplicity, this research considers principles from both these initiatives.

Compared to natural and behavioural science, which tend to deal with problems related to “seeking the truth”, Design Science deals with problems related to “seeking what is effective”. Constructivism or behaviour science also has its place in Information Science, especially in identifying organisational behaviour, user acceptance or effectiveness while implementing an information science solution. Hence, once an artefact (construct, theory, framework, etc.), has been created

through Design Science, the subsequent stages of its implementation and evaluation in the organisation can be carried out using principles from behaviour science.

Wherever possible, further details into the research method applied to a particular part of the research are provided, especially in the evaluation section.

3 Problems with the Production Management Systems: Understanding the problem and the context

3.1 Problem Awareness: Observations from the industrial practice

In design science, the researcher starts with a practical problem at hand, explores the problem area further to create detailed awareness and develops a solution to overcome that problem. This research also started with a very practical problem that the researcher had encountered while working within the construction industry.

The following section discusses the problem and presents the context for the research and the solution developed. To preserve anonymity of the organisations presented, their details are not mentioned in the discussion. One company was based in India while the other was based in the UK. The author had the opportunity to make close observations over a period of time, which contributed to some of the early understanding of the problem as described below.

3.1.1 Observations from Company A

The observations were made during the implementation of an internally developed Enterprise Resource Planning (ERP) system within a construction company. One of the core purposes of the new ERP system was to increase efficiency of individual functions that were being served, as well as providing integration between various departments located at separate geographic locations. Company A had developed the ERP system internally by hiring a team of Software Developers who were led by the IT manager and helped by the MIS (Management Information Systems) Manager.

The implementation process had initially experienced problems, as the users of the system had not accepted the system in its current form due to problems with user interface, missing features and incorrect processes. After some initial analysis it emerged that the users had not been consulted in the first place when the system was being developed leading to subsequent problems.

The Enterprise Resource Planning system consisted of the following modules:

- i. Procurement
- ii. Asset Management
- iii. Stores/inventory
- iv. Human resources
- v. Accounting
- vi. Payroll

The following major observations regarding the ICT systems were made at Company A:

- The information integration between various functions (which was the core parts of the system) had still not been achieved even after the full implementation. This resulted in duplication of data entry at several points.
- One of the main observations made was that while the peripheral functions of this construction company were addressed with the ERP modules listed above, the very core of the business – the production (or construction) process itself remained unaffected. As a result each project manager was left to devise his or her own system. Many developed their own solutions based around manual paper based documents and Excel Spread sheets. However, these individually designed systems remained completely isolated from the ERP system and hence the information availability at production level was absent. As a result, traditional communication channels of telephones, faxes, and emails were utilised to obtain production related information.
- When the candidate visited the organisation after 9 years, it was observed that even as the organisation had implemented new features such as electronic procurement and provided access to some construction projects to the ERP system, the actual production management process still remained unaffected and relied on individually devised systems.

3.1.2 Observations from Company B

Company B had been using an ERP system that was not being supported actively by the software provider any longer and was obsolete. As a result the company B was looking for a new ERP system to suit their business and was undergoing a

review to ensure that their business processes were ready for this new implementation.

The following ERP software modules were implemented:

- Payroll
- Human Resources
- Procurement
- Subcontractor ordering
- Accounts

The following observation was made at Company B:

- It was found that the existing information systems and processes (prior to the implementation of the new ERP system) were not integrated, especially across departments. There were major bottlenecks between departmental processes that resulted in delay in overall operation. This phenomenon has been documented as “islands of information” (Bowden et al. 2006). However, it was found that even after the implementation of new ERP system many of these problems still remained.

Despite this major implementation of software system that nearly cost £0.5 million, the production management processes remained almost unchanged; while some of the problems observed with the construction processes are documented below.

- As majority of work was executed using Subcontractors (there were no direct construction workers employed by the company), managing Subcontractors was a major task. Processes range from Prequalification, Subcontract Tendering (during bids), Procurement, Quality, Safety and most importantly Production (coordination). It was identified that there were at least five separate subcontractor databases being used and maintained by individual departments, namely estimating, accounts, quantity surveying, safety and quality.
- None of these databases were synchronised with each other and hence caused significant duplication in efforts. Also, due to this lack of

synchronisation, significant problems related to production management arose. For example, subcontractors who were blacklisted due to bad safety records were routinely selected by QSs and Estimators to work on projects. The accounts department routinely queried the QSs regarding particular bills as they had no records of work from projects.

- One of the other major problems identified was that of reconciliation of materials received and payment to suppliers at site using “Goods Received Notes” (GRNs). The GRNs are a record of the goods received on site against purchase orders. They record the item description, purchase order number, supplier name, date and quantity received. Any discrepancies between the purchase order and items received at site are noted here to ensure that correct payments can be made. It was observed at company B that there was a general lack of integration between the information systems used by procurement, accounts and the construction sites. This resulted in 80% of the GRNs being queried for a number of reasons. This not only caused delays in the payment to suppliers, it also resulted in significant time wasting for both accounts departments and project managers. Some of the reasons are outlined below:
 - As the working conditions on site are not controlled as the office environment, the condition of the GRNs when they reached accounts was on many occasions quite poor. Hence, they were not legible and further clarification was required.
 - If the quantity between the purchase order and supplied quantity on site were different.
 - Material supplied without a purchase order number

Although the problems outlined above are quite significant, one of the most fundamental issues was that (similar to Company A) the core production management systems and supporting functions remained almost unaffected by the existing or new information systems. As a result the inefficiencies present in the construction process remained unaddressed. Hence, each construction project would need to define its own production planning, scheduling and control

processes and also manage the implementation of information systems to support them, giving rise to some critical problems, which are outlined below:

- Communication and management of project information remained a critical issue. Around 10 projects were studied where it was found that almost two hours were spent daily to manage emails where almost 50-60% of that information was duplicated. Even after implementing a dedicated extranet (project information system) the problem remained, as the information remained isolated from the production system.
- Drawing Management: Majority of the design and production information received was either through paper or CAD drawings. These were scanned and/or then printed and sent off to sites via post by Head Office. As design changes can be frequent the process remained quite intensive and the volume of drawings remained quite high. This caused significant costs in postage. Also, there was a major communication problem as it was not always possible to ascertain whether all subcontractors were working with the latest copy of the design/drawing/specification. The following incident occurred as a result:
 - During a project a subcontractor claimed not to have received the latest version of the drawing, which led to a major incident on site leading to collapse of a structure. However, due to the lack of an electronic audit system, it could not be proved whether the subcontractor had or had not received the drawing.
- There were a number of general information management related problems identified, as the existing and newly implemented ERP system still did not address some of the core functions of the organisation. For example, the Prequalification, Safety and Quality Management processes for managing the supply chain were simply not supported by any information systems. This resulted in significant problems, with major duplication of efforts, information bottlenecks causing delays on projects, and inefficiencies related to poor information availability at the production level.

- During a recent discussion with the IT Manager of the company, after 5 years of implementation, many of the problems identified and reported previously still remain.

3.1.3 Summary – Problem Awareness

It was observed that through the implementation of Information Systems, a number of improvements were made to the peripheral processes, communication between external and internal stakeholders and partially to the production management processes. However, major inefficiencies were still found with the integration of information and in the production management itself. The performance of the projects following the implementation of new Information Systems did not show any major sign of improvements. This shaped some of the early understanding of the practical problem that were then further explored through literature review, case studies and focus group interviews, which is discussed in subsequent sections in this Chapter.

3.2 Problems with production management in construction – observations from literature

There has been extensive research into the causes behind the problems faced by the construction industry over the years. A number of such causes have been identified, for example, contractual problems, theoretical problems, inefficient production management systems, ineffective product representations and specifically the unsuccessful use of IT. The scope and focus of this research is on production management in construction specifically, hence a detailed review of the problems facing the production management processes has been carried out.

Navon and Sacks (2007) have reported about the requirements of information management in production management and control. They report that production facilities require control processes in order to produce desired products. The control processes involve bi-directional flow of information – forward flow to direct the behaviour of the process, and feedback information from the process to the controlling function. They criticise the monitoring system in construction industry as slow and primitive and put forward the following as main reasons:

- i. Dynamic project systems for construction product delivery

- ii. Ad-hoc organisation of disparate companies with limited or no long term working relations
- iii. And the control processes relying on manual data processing methods which are slow, inaccurate and expensive

Formoso and Isatto (2008) describe the main flaws in production management as following:

- Production management and planning is interpreted simply as preparing a Gantt chart (such as in CPM), and not much effort is made to synchronise accurate project information (Laufer and Tucker, 1987). The synchronisation of production information is made even more difficult due to several organisations involved in a single project, where in most cases each stakeholder uses their own information systems.
- There is a general lack of formal systems dedicated to the control aspect in production management, where it usually depends on verbal exchanges between site teams and supervisors/managers. Control is also dependent on short-term decisions and is seldom linked to long-term plans, which contributes to a number of problems, especially in case of resources with long lead times and custom engineered components, which are made to order (Formoso, 1991).
- Many construction companies tend to emphasise the control related to global project aims, and fulfilment of contracts, rather than production control. In this context, spotting problems in the production system and defining corrective lines of action often become problematic (Ballard and Howell, 1997).
- Unpredictability is a common problem in construction planning especially due to dynamic site conditions, however is still not recognised in the production management system. Hence, the necessary means to overcome or address uncertainty are absent from the production management systems (Cohenca et al., 1989). This is also reflected in the fact that in construction projects, detailed long term plans are prepared which become obsolete from start, and to keep such plans updated becomes a highly time consuming affair (Laufer and Tucker, 1987).

- Information and communication technology (ICT) systems have not been very effective in production planning as they are mostly procured and implemented without assessing and identifying users' requirements. This leads to further instability in production management and creates waste through irrelevant and large amount of information that do not support proactive elimination of problems but only informs about them (Sanvido and Paulson, 1992). Traditionally, information systems are implemented in an isolated fashion where they are not integrated with other internal or external systems. User training and awareness in using advance information system also remains a problematic issue (Turner, 1993).
- Due to some of the problems outlined above, such as a lack of a systematic approach to synchronise and present production information and also due to the "T" based approach in management, most construction managers rely on their own experience, intuition to take decisions leading to further uncertainty (Lantelme and Formoso, 2000).

The following section discusses these and additional problems related to production management in construction in further detail.

3.2.1 Product and Process Visualisation:

One of the largest problems in production management is that of insufficient visualisation of project information (Kymmell, 2008). The visualisation of project or production information can be classified in two categories, i) process visualisation; and ii) product visualisation. The problem of visualisation spans the entire lifecycle from design to construction, handover and facility operations and maintenance. For example, if the client requirements are not fully visualised, understood and communicated, they cannot be represented correctly in the design and specification and leads to subsequent problems during construction and operation of a facility. Similarly, difficulties in visualising production related information in the right context creates significant problems during the production planning and execution stage. The production related information encompasses:

- The process related information such as that of input flows – i.e. material, equipment, labour, connecting works, space, etc.,

- Product visualisation – i.e. information regarding what is to be built, the information that is usually referred as design information and consists of 2D CAD drawings or 3D BIM models, and also includes information, such as quantity, specifications, fitting instructions, etc.

dos Santos et al. (1998) defined transparency of the process as “the ability of a production process (or its parts) to communicate with people”. The authors add that the implementation of transparency at the organisational and at the operational level in the form of simplification, motivation, rapid understanding of information and such is quite advantageous (Greif 1989).

Formoso et al. (2002) have compiled a list of benefits of process transparency relevant from the construction perspective:

- i. In workplaces where the layout changes frequently, effective location information aids people to identify workstations and pathways.
- ii. Display of information at the workplace improves the effectiveness of production planning and control.
- iii. Visual communication tends to increase the involvement of workers in continuous improvement efforts since it allows rapid comprehension of and response to problems.
- iv. Control is simplified, reducing the propensity for errors and making them more visible.
- v. Process transparency has a positive impact on motivation.

However, despite the advantages, the construction industry is far behind in use of such principles and have very few visual mechanisms to inspire, instruct or motivate workers to carry out their jobs more effectively, efficiently and safely (dos Santos et al., 1998).

3.2.2 Unavailability of production related information at the “coal face”:

Project managers, site managers and foreman (and in general the construction team) rely on accurate and up-to-date (real-time) information about production to manage the project and resources. The absence of real-time production management systems – systems that provide a complete set of production

management related information makes this task cumbersome and inefficient where a significant amount of time is required to extract information from various sources (such as extranet, intranet, ERP systems, emails, faxes and other mean of communication). It also reduces their ability to manage the variability and uncertainty inherent in project activities. (Navon and Sacks, 2007, Howell and Koskela, 2000). A survey carried out by Fruchter (2001) reported that the need for the data entry at the project level is one of the biggest bottlenecks to the success of the production management system as a whole. Research carried out by McCulloch (1997) reported that, on average, 30-50% of the time of construction personnel on site is spent in recording and analysing production related data. However, on a practical level, there has been little progress to help construction teams efficiently handle data collection and provide timely and accurate information (Navon and Sacks, 2007). This problem is explored further in detail in section 3.4.

3.2.3 Problems with the integration of supply chain

The UK construction industry is highly fragmented with a large number of small companies operating in the sector. Over the last 30 years the industry has increasingly grown risk averse and relies mostly on subcontracted workers to execute projects. (Dainty et al., 2001). Figure 7 shows the distribution of the construction firms in three major European countries – UK, France and Germany (compared with USA). Figure 7 below shows that almost 90% of the firms operating in the country are micro organisations (1-9 employees), and 9.4% are small (50-249), where the Large and Medium size only form 0.7% of the overall proportion. This demonstrates the amount of fragmentation that exist within the UK (and European) construction sector, and the challenge it poses especially from the integration perspective. As recognised above, production management requires communication and availability of information at the crucial stages of production. This information is often generated from and has to be communicated across the supply chain. The severe fragmentation present in the supply chain makes it increasingly difficult for this information to be synchronised and communicated at the right time. Dainty et al. (2001) report that the UK construction sector is a long way from being able to achieve true supply chain integration and that an adversarial culture is ingrained within industry's operating

practices, where a general mistrust between companies prevail. This raises further dimensions to the existing problems of production management and control.

Proportion of Firms by Size Category				
<i>Size (No. of Employees)</i>	Micro (1-9)	Small (10-49)	Medium (50-249)	Large (250+)
GB ¹	89.8	9.4	0.6	0.1
France ²	91.6	7.7	0.7	0.1
Germany ²				
Structural Firms Only	69	27	3.7	0.4
All Construction Firms	95			
US	81.1	16.3	2.4	0.1
1. Size bands for UK are 1-7, 8-59, 60-299, over 299				
2. Medium Size Band 50-199				
<i>Source: DTI, Hauptverband der Bauindustrie, Service, Economique et Statistique, US Census Bureau</i>				

Figure 7. Proportion of UK Construction Firms by Size (DTI, 2004).

Since early 1990s research into the supply chain management structure of construction industry has been on-going with a view to explore the possibilities of transferring manufacturing concepts to construction in order to improve production efficiency and reduce project costs (Azambuja and O'Brien et al., 2008). However, construction supply chains are distinctly different from manufacturing sector and direct applications of management principles may not be possible. This is made evident in recent studies carried out by Vaidyanathan and O'Brien (2003); Green et al. 2005; and London and Kenley (2001), where the authors have highlighted key differences and opportunities in applying manufacturing concepts to construction from a supply chain perspective. Azambuja and O'Brien (2008) provide a summary of the key differences between manufacturing and construction supply chains as shown in Table 2.

Table 2. Manufacturing vs. Construction Supply Chains (Azambuja and O'Brien et al., 2008).

Characteristics	Manufacturing Supply Chains	Construction Supply Chains
Structure	Highly consolidated High Barriers to entry Fixed Locations High interdependencies Predominantly global markets	Highly fragmented Low barriers to entry Transient locations Low interdependencies Predominantly local markets
Information Flow	Highly integrated Highly shared Fast Supply Chain Management Tools (factory planning and scheduling, procurement, planning)	Recreated several times between trades Lack of sharing across firms Slow Lack of IT tools to support Supply Chain (no real data and workflow integration)
Collaboration	Long-term relationships, Shared benefits, incentives	Adversarial practices
Product demand	Very uncertain (seasonality, competition, innovation, etc.) Advanced forecasting methods	Less uncertain
Product variability	Highly automated environment (machine, robots), standardisation, production routes are defined – lower variability	Labour availability and productivity, tools, open environment (weather), lack of standardisation and tolerance management, space availability, material and trade flows are complex – higher variability
Buffering	Inventory models (EOQ (Economic Order Quantity), safety, etc.)	No models Inventory on site to reduce risks Use of floats (Scheduling)
Capacity planning	Aggregate planning Optimisation models	Independent planning Infinite capacity assumptions Reactive approach (respond to unexpected situations, for example, overtime)

Azambuja and O'Brien (2008) note that the terms like buffer, variability, and uncertainty are not yet common among experienced construction managers. However, on-site production inefficiency is often caused by poor production planning (which includes decisions on buffers) and limited planning concerning the impact of off-site production and delivery variability. To mitigate the risk of variability the common practice is to amass vast inventory of resources including space, material, labour, equipment and even production tasks, which is a form of a major waste.

The increase in complexity of construction projects and market dynamics, results in increase in the level of fragmentation. This creates further difficulties in coordinating the supply chain as (Azambuja and O'Brien, 2008):

- The number of planning activities and alternatives increases dramatically;
- Divergent stakeholder interests need to be managed (Wiendahl et al., 2005);
- Lack of understanding of the project by different participants (Formoso et al., 2002)

It emerges from the above that the supply chain management, especially the fragmentation of the supply chain, and the temporal, site based production in construction creates significant problems from production planning and control perspective.

Sacks et al. (2010) describe factors that make coordination between subcontractors, material and equipment suppliers, construction management personnel, designer and inspectors difficult as:

- Physical dispersion of the teams within the building or across the site where they are usually hidden from one another by the structure itself
- Contracting relationships with remuneration terms that encourage local optimisation and work against overall project organisation
- Complex variations in productivity rates, which make it very difficult to predict short term progress
- Lack of effective real-time reporting of progress, despite multiple research efforts aimed at automating this aspect of project control
- Dependence on key individuals to obtain and communicate critical information regarding constraint status to the look ahead and last planner functions
- Reliance on paper documents to communicate product information, with the limitation of design documentation errors, lack of clarity and potential obsolescence of information

It is worthwhile to note from the above discussion that the last three points point towards problems with information management, and show interdependencies between the problems behind the production management. Also shown in Table 2 above, information flow aspect is quite poorly handled in the construction supply chain. The information is handled several times creating waste; there is a general lack of information system to support the production; and there is in general the lack of integration between supply chain members. This problem of integration from an information systems perspective is discussed in detail further in section 3.4.

3.3 Root causes behind the problems

As much as it is important to identify and discuss the problems behind the production management process, it is equally important to understand what are the causes that contribute to these problems. There are a number of reasons, which contribute to problems within the industry. Once we identify the causes behind the problems, it is then possible to research the solution to overcome the problems. The major causes behind the problems regarding the production management and control processes reported above are discussed in the text below.

3.3.1 Current construction theory

Koskela and Vrijhoef (2000) argue that the one of the most fundamental reasons behind the problems within the construction industry is the current theory behind construction, which is implicit and deficient. It is argued by the authors that as the theory behind construction is implicit, it is not possible to directly transfer innovative concepts such as lean manufacturing and mass customisation. Also, the lack of an explicit theory prevents access to the core concepts within construction. This in turn makes it difficult to create new templates for transfer of concepts such as lean manufacturing.

Koskela (2000) also argues that the prevalent theory behind construction is the one of transformation view of production. The transformation view of production means:

- A project can be decomposed into parts and further decomposed to tasks.

- It is assumed that the project can simply be managed by assigning tasks to workers and making inputs available
- Also by minimising cost of each sub-component it is assumed that the project cost can be optimised.

In the transformation view of production, there is no place for variability or time. It is well understood that a construction project is a highly dynamic environment where variability is abundant; hence the transformation view proves highly counterproductive. Here, no emphasis is given to the flow (“F”) or value (“V”) aspect of the process. In reality, flow and value are also important aspects of the construction process, as no process is performed in isolation and several resource flows such as material, labour, space, connecting works and external conditions are affecting the process simultaneously. Also, the value aspect helps keep the customer and their requirements in forefront, as for any project; it is the customer who should be the ultimate focus.

Koskela (2000) also argues that taking this view has led to a new waste in construction, which is referred to as “making do”. Here negative buffering takes place; i.e. tasks are started without all necessary inputs are in place. This is one of the most common waste on construction projects according to Koskela (2000) as construction workers often seek innovative ways to solve problems arising due to the neglect of the flow aspects of construction. “Making do” will be discussed further in Chapter 4.

The lack of theory behind construction and the predominance of the “T” view on construction has not only caused hindrance in understanding the construction process in needed clarity or to innovative solutions being applied, it has also contributed to inefficient project planning, scheduling and control methods. Similarly the effect of “T” view of production is extended to supporting and enabling systems such as Information and Communication Technology systems that support the construction industry (Dave et al., 2008). The inefficiencies of the production planning, scheduling and control methods and the problems with the ICT systems are discussed in the subsequent sections.

3.3.2 Production planning, scheduling and control methods

Production management comprises of three distinct activities, planning, scheduling and control (Ballard, 2000). Construction is often criticised as an industry, which lacks streamlined processes and a standardised production management system (Egan 1998, Latham 1994, Wolstenholme, 2009). On most projects, managers and site personnel are left to devise their own production management and control system. In the situation where the teams are efficient and experienced the project indeed benefits and delivers good results. However, it can be said that on other occasions the ad-hoc implementation of processes creates chaos and results in time and cost overruns.

3.3.3 Planning in production management

Traditionally, in construction, planning is considered to be an equivalent of creating a Gantt chart of tasks to be performed (Henrich et al., 2005). This Gantt chart on most occasions is created at the early stage of the project at the head office without consulting the project team (Ballard, 2000). At this stage of the project the reliability of information, i.e. resource availability, external conditions, client changes are not yet available and hence the reliability of the plan is quite low (Ballard, 2000). However, this master plan is taken as the base document and pushed to the site team to be followed regardless of the current situation on the ground. The other shortcoming of this plan is that it seldom shows various flows of resources such as labour, equipment, material etc., hence the site team has to decipher this detail on their own. From the discussion about current ICT systems, it is observed that not many organisations have achieved complete integration between their information systems, and this leaves the site team without the critical information regarding these resources during the execution of the project. Also, most planning methods do not include the spatial information in the plan, i.e. it does not show where the work is going to be carried out and how resources will flow during the project (i.e. smooth flow of resource between locations without interruptions). This leads to resource clashes during the execution; i.e. two work teams working within the same space, material being stacked too far from the project, not knowing where the equipment are or when they will be available. All such factors add to the inefficiencies during the execution stage. In the following

paragraphs some of the main production planning and control systems being used in construction will be discussed.

3.3.3.1 Critical Path Method (CPM)

The CPM method was developed by DuPont and Remington Rand around 1957. It was developed to mathematically calculate the sequence of activities in order to complete a project in the minimum time possible. CPM programmes show activity dependencies and duration allocated for each activity. It also allows for calculating the float of an activity, where float is the amount of time a non-critical activity can be delayed without affecting the overall programme. A majority of construction projects today use CPM as the main project management, planning and controlling mechanism. It is the most popular method in construction over the last five decades. The project plan is shown using Gantt charts, which are the visual representation displaying activities as horizontal bars where time is plotted on the X axis. Due to this visual representation, Gantt charts are quite easy to understand and have made the CPM method very popular amongst construction professionals.

The CPM method can be seen as the direct implementation of the transformation view. It implies that by breaking the tasks into smaller chunks or by way of work breakdown structures, a project can be managed. The aspects such as flow of materials, labour, equipment or information are not taken into account (Howell & Koskela, 2000). CPM is effective in providing a big picture but if one tries to add information such as material and labour flows, it starts to get very cumbersome and difficult to manage (Peer, 1974; Birrel, 1980). Also, one further essential element that is missing from the CPM method is spatial information (i.e. smooth flow of labour and resources between locations). It is understood that construction takes place in space and time. CPM addresses the time element (although not in a complete way); the spatial element is completely missing. If one tries to add a spatial element, i.e. where a particular task will be carried out, the Gantt chart starts becoming too complicated and as a result, is seldom updated. The consequence is that without the spatial element, the programme becomes difficult to manage; as it frequently leads to resource clashes, i.e. Two labour teams working in the same place at the same time where there is not enough space,

material being stacked in the wrong place, crew sitting idle as there is no space or direction where they should work next, etc.

3.3.3.2 Line of Balance (LOB)

Line of Balance is a linear scheduling method, which shows the tasks in a project as a single line on a graph as opposed to a series of individual activities on a bar/Gantt chart. It is mostly used on projects where there are a number of repetitive activities such as a housing or a road construction project.

LOB was originally developed by the Goodyear Co. in the early 1940s and was further developed by the US Navy in the early 1950s for programming and control of both repetitive and non-repetitive projects. (Turban 1968; Lutz & Halpin, 1992). The LOB technique assumes that the rate of production for an activity remains uniform during the execution time. Most commonly, time is plotted on the horizontal axis where as work units are plotted on the vertical axis. The resultant chart shows sloping lines, which represent the production rate of an activity. Another characteristic of the LOB is that it represents work activities being continuously performed, even if the work is being carried out in different locations.

Recently, Seppänen (2009) has attempted to improve the location based planning tools and their processes. In the research, the author implemented the location planning methods on three case study projects and studied their performance. It was observed on the case studies that, even after project activities were subjected to cascading delays from an initial phase, the actual finish date of the project was not affected. This was due to the long end-buffer that was put in the schedule. Also, the author found that the problems occurring on projects could be envisaged earlier due to the location-based control data available.

LOB partially addresses the issue of spatial information, as there is a possibility to show the space where the task will be carried out over time on the activity line. However, there are limitations to this approach as it works well in projects where there are repetitive tasks, as LOB does not work well where the project has many unique tasks. Also, the issue of temporary structures is not addressed by the LOB method. A typical construction project during their lifetime see erection and

demolition of many temporary structures, which have to be managed during the planning and execution stage. As these are unique in nature the LOB approach does not work well in this case. The simple nature of the LOB charts also limits the amount of information that can be shown on them.

3.3.3.3 Critical Chain

Developed by Goldratt (1997), Critical Chain Project Management (CCPM) is a method of planning and managing projects that put the main emphasis on the resources required to execute project tasks. As opposed to other methods such as CPM, which advocate rigid task order and timeline based scheduling, Critical Chain requires the schedule to be flexible and tries to keep resources level throughout the project. Overall, it focuses on taking out the individual task “float” or “buffer” and allocating them to one big collective buffer. It assumes that this way the tasks are started as soon as the previous one finishes and project completes on time. The Critical Chain theory is based on the Theory of Constraints developed by Goldratt (1997) which is based on the premise that rate of goal achievement is limited by at least one constraining process. As described by Goldratt (1997) the five key steps in organisational/process improvement are:

1. Identify the constraint (the resource or policy that prevents the organization from obtaining more of the goal)
2. Decide how to exploit the constraint (make sure the constraint's time is not wasted doing things that it should not do)
3. Subordinate all other processes to above decision (align the whole system or organization to support the decision made above)
4. Elevate the constraint (if required or possible, permanently increase capacity of the constraint; "buy more")
5. If, as a result of these steps, the constraint has moved, return to Step 1. Don't let inertia become the constraint.

Koskela et al. (2010) have compared the Critical Chain Production Management to the Last Planner System™ within the context of construction management. The authors summarise that while Critical Chain endeavours to shorten the project duration with cost reductions (where other benefits are secondary), Last Planner primarily endeavours to reduce the variability in work flows, which directly leads

to increased productivity and cost reduction along with gains in safety and quality. In addition, Last Planner helps with schedule compression as it reduces variability. In criticism, Koskela et al. (2010) mention that the Critical Chain method is restricted to buffer management, as it does not try to address/reduce the cause of the buffers or variability. Hence, there is a limited scope for productivity improvement through variability reduction. In comparison, Last Planner fails to maintain an explicit link with the master plan (Junior et al., 1998), hence the current situation on site can not be readily assessed from an overall project perspective. Also in Last Planner there is no direct method of schedule compression at the master plan level.

3.3.3.4 Last Planner

The Last Planner™ system (Ballard, 2000) – as the name suggests is based on the planning and scheduling that is carried out by the people responsible for the execution of work, i.e. site manager, foreman and work crews. Traditionally, planning and production management is carried out with a top-down approach. Planners mostly based at the head office prepare the schedules right at the estimating stage. This is then pushed to site teams to follow during the entirety of the execution stage. Very little input window to planning is left for the site teams. As discussed, this makes the execution plans quite unreliable, as they are prepared when there is not much reliable information available.

Last Planner tries to overcome problems of traditional planning methods by introducing shorter planning cycles during the execution stage, which are prepared by the work teams and are based on work commitments on “what CAN be done” rather than “what SHOULD be done”. Here, the master schedule is taken as a guideline, and informs the work teams about major milestones and overall schedule. Based on the master schedule a look ahead plan is prepared 4-6 weeks in advance, which is based on the current resource situation and up-to-date forecasts. Further to this, weekly meetings are organised where all work teams take part and “pull tasks” from the look-ahead plan. Also, the weekly meetings are used to analyse the reasons for non-completion for previous week’s tasks, and a task is only selected if all the pre-requisites to starting that task are met. This clearly improves the reliability of the planned work and improves the efficiency of

workers. The method also builds a network of promises, as each week, all stakeholders commit to the work being planned and are then held responsible for the same. This gradually builds the trust and improves social environment (collaboration) on site as all units operate as a team.

Last Planner takes into account the flow aspects of the construction process during the execution stage. It has generally been found to improve the reliability of the projects due to the increased reliability of the plans. Here the responsibility of production control shifts from the top level to the comparatively lower ranks as the work is pulled based on all the prerequisites being met. On the other hand, commitment to the method becomes a prerequisite for all parties. As a result, last planner may not work properly in situations where it is not possible to create a network of trust. Also, in organisations where the control is mostly kept in top circles, the managers find it too difficult to allow the site team to control the production process. Again, in cultures where this is the case the system might not work in its current form (i.e. it may need adapting to suit the cultural and process issues).

Even though the Last Planner system takes into account the variability in the process, it does not go beyond the weekly planning meetings. A construction project is a dynamic environment and much could happen/change during the span of a week. Reliability can be further improved if a shorter planning cycle is introduced (Sacks et al., 2009).

3.3.3.5 Summary of planning methods

Despite its shortcomings CPM remains one of the most popular methods being taught and used in the academia and the industry. The majority of construction planning and scheduling software are also based around CPM. The linear scheduling methods help in selective projects but cannot provide an overall solution to the industry. Critical Chain is not yet followed in the mainstream construction and is undergoing further research. It has some parallels with the Last Planner System, and it can be argued that they complement each other well. The Last Planner™ system of production management and control is beginning to become popular where there is a reasonably supportive environment for its implementation. It can be concluded that there is a need for a streamlined

construction process through a systematic implementation of a production management and control system which takes into account the transformation, flow and value concepts.

3.4 Information and Communication System Problems in Construction

Managing production related information is critical for construction projects as discussed in section 3.1 above. It was also observed in 3.2 that due to relatively deep and complex supply chain on construction projects, it is critical to ensure effective communication between the parties to enable smooth and error free production planning, scheduling and control.

Information technologies have been evolving at a rapid pace in the last two decades. Especially, the Internet revolution in the 90s has led to a significant shift in business and industrial processes around the world (Howard et al. 1998; Rivard 2000). This has led to organisations investing heavily in technology implementation in terms of hardware and software solutions. The same can be found in the construction industry. The growing trend of ICT implementation within construction is reflected in various surveys carried out around the world (Arif and Karam, 2001; Samuelson, 2002; Ingirige and Aouad, 2001; Issa et al., 2003; Tas and Irlayici, 2007). However, recent literature and research has shown that the industry has not yet been able to gain the desired benefits from ICT projects. (Pena-Mora et al. 1999; Tatari et al. 2007; Nitithamyong and Skibniewski 2003). Frustrations related to Information Systems implementations are not limited to the construction industry alone. Legris et al. (2002) have reported that only 26% of all MIS (Management Information Systems) projects are completed on time and within budget, with all requirements fulfilled. Some of the reasons behind this lack of effectiveness of the ICT systems to bring desired benefits are explained below.

3.4.1 Shortcomings of the current design and product modelling systems:

Construction drawings (2D) have been traditionally considered to be a language with which professionals within construction industry communicate. In the 1760s, a precise standardised method for representing three dimensional objects called descriptive geometry in two dimensions was developed by the Frenchman

Gaspard Monge (Koskela et al., 2010). The method was deemed so powerful that it was kept in secrecy for many years, and Monge published the details only in 1799 (Kant, 1799). Since then, descriptive geometry has been the basis for construction design drawings. Together with written description, such as bills of materials, drawings have been used to represent the object to be built, both for contractual purposes and for site execution (Koskela et al., 2010).

A number of Computer Aided Design (CAD) software have been developed over the years, which facilitate generation and distribution of drawings. However, due to the fragmentation prevalent in the construction industry, the ability to interpret these drawings on a project varies from one subcontractor to the other. Also, due to increasing complexity of building systems, drawings have become much difficult to interpret even for the technically competent. Computer Aided Design does not intrinsically support generation of intelligent design, whereas the objects contained within the drawings demonstrate behavioural patterns and where design objects can be controlled in a parametric way.

Current practice in using 2D CAD is that the designers and engineers develop solutions independent of each other. However, there is no potential solution to automatically check the design for consistency, and due to complexity of design, manual checking is quite difficult. This leads to design errors and inconsistencies, which are then identified on site and are costly to fix. Also, it is not possible to automate tasks such as fabrication using CNC systems using CAD drawings, or to check the design for potential clashes between various components such as building structure and facilities. It is also not possible to build fail-safe rules (design templates to ensure standard conformance) using 2D CAD systems.

On the contrary, object oriented design development, which is offered by Building Information Modelling software, is capable of representing intelligent behaviour and can integrate a multitude of information from various sources. (Eastman et al. 2008).

The problems with the traditional 2D CAD technologies during the construction project lifecycle are discussed below. The stages described below could be different in sequence depending on the type of the contractual agreement, for

example Design-Bid-Build or Design-Build. In Design-Build and partnership projects, some of the inefficiencies of the traditional process described below are taken care of, however, the critical inefficiencies related to the production phase most likely remain.

3.4.1.1 Problems during Pre-Construction

The key goal of the conceptual design stage is to capture the functional and aesthetic requirements from the client and translate that into design intent. This makes design a highly iterative process, where initially a significant amount of refinement is taking place and client input is being taken into account. The current paper based process leads to significant inefficiencies, as it is not easy to interpret and communicate the design intent about a three dimensional space in a two-dimensional drawing (potentially for an untrained eye of the client). Also, through the paper-based process, critical project based information such as cost estimates and performance evaluation (such as energy, acoustics, structural, thermal, etc.) has to be carried out post design and manually. Often, when inefficiencies are found with the design, it is too late to make a change, which then leads to compromises with client's original intentions.

3.4.1.2 Problems during Tendering and Bid Process

Traditional contracts based on the lowest bid, involve a strenuous bidding process, where contractors spend at least 1% of the estimated project costs on compiling bids (Eastman et al., 2011). These bids are developed using paper based or electronic 2D drawings, where manual extraction of quantities and interpretation of design is required. As a result, significant amount of time and effort is required in preparing the bid. If we consider a contractor's hit rate as 20% (i.e. they win 1 job for every 5 bids), the 1% of bid development cost gets added to the overheads. Also, due to major inconsistencies in design, a significant amount of RFIs are generated even during the bid stages as the main contractor has to take input from their supply chain to arrive at a final cost.

3.4.1.3 Problems during Design and Detail

Developing a detailed design is a highly collaborative and iterative process, where a number of design consultants contribute towards the final design. The current 2D CAD and design processes do not lend themselves for collaborative design development. Most commonly an over-the-wall approach is taken towards design where each consultant (Architect, Structural, MEP, etc.) develops their respective design and passes it to the next as an input. This makes the process a very lengthy and costly. Also, due to the fragmented nature of design development, many issues related to physical clashes between different design elements (i.e. architectural and structural or structural and MEP etc.) remain undetected until the construction stage of the project. This leads to either rework or lengthy delays during the construction process.

A study carried out by Freire and Alarcón (2002) diagnosed and evaluated the traditional design process for three projects of a design consultant. The authors used lean principles to identify wastes present within the process and found the main wastes occurring within the process to be:

1. Ignorance of client requirements;
2. Bureaucracy and paper work;
3. Interdisciplinary coordination;
4. Information not available; and
5. Rework.

Freire and Alarcón (2002) also identified time distribution in traditional design process as shown in Table 3 below:

Table 3. Distribution of time in design tasks (Freire and Alarcón, 2002).

Category	Duration (%)
Designing	50.2
Verifying information	8.2
Collecting information	28.1
Correcting information	12.2
Issuing	1.4

The results from table above clearly show that the value adding activity of actual design work contributes to only 50.2% time spent on this overall process, where the rest constitute wasteful tasks.

3.4.1.4 Problems during Construction Phase

It is during the construction stage that the inefficiencies of the traditional design cause the biggest problems (Eastman et al., 2011, Kymmell, 2008).

- **Rework due to inaccuracies or lack of detail:** As the design is not normally checked for constructability and refined for execution, a thorough review takes place early in the project to identify errors and omissions.
- **Lack of support for Prefabrication:** Also, the lack of automation and parametric abilities of the 2D design makes it difficult to support a prefabrication strategy; hence most of the components have to be constructed on site, leading to inefficiencies.
- **Clashes leading to rework:** Two types of clashes could occur, physical clashes; i.e. construction elements clashing with each other as design hasn't been refined or process clashes; where the work sequence hasn't been properly planned due to lack of visualisation. This causes either a delay in work or complete rework of construction elements.
- **Drawing Management:** Drawing or design issue management becomes highly complex and inefficient in a 2D CAD/ paper based process. This leads to not only inefficiencies on construction projects, but also causes safety issues as probability of subcontractors working with a wrong revision of drawings increases. On a case study A a major accident happened where a subcontractor used an old revision of drawing to construct a concrete slab. This led to the failure of the slab and injury of two personnel. The subcontractor claimed that they had not received the latest copy of the drawing. Also, on an average it was found for company A that the expenses for postage and scanning of paper drawings were in the region of £200-£300 (excluding personnel costs).
- **Visualisation of design during planning:** It is highly important that the production teams and project managers are familiar with the design and

complexity of tasks while planning and scheduling production tasks. However, with 2D drawings it becomes quite difficult to visualise 3D spaces and how the production will happen over a timeline, especially if it is a complex structure. Also, quite often it is realised during the project that required information from drawings and specifications is either missing or not clear. This leads to significant number of Requests for Information (RFIs) being sent to and from the project. It is widely documented that RFIs lead to major inefficiencies during a construction project.

3.4.1.5 Problems with Handover and Post Construction

There are two important issues the project has to address:

- Handing over an accurate record and information about the facility to the owner
- Ensuring the information handed over supports effective operation and maintenance of the facility

Normally at the end of a project, all the as-built information is sorted and archived in boxes, which are then handed over to the client. However, as the information is mostly recorded on paper, this resource is hardly ever used or synchronized with a client's facilities management system as demonstrated in the Maryland General Hospital case study, which was documented by the author (Eastman et al., 2011). The following observations were made in the case study:

- The lifecycle of the equipment was not optimized, i.e. the facilities management system did not take into consideration issues such as maintenance intervals, servicing, etc.
- Warranty and other product-related information were not easily accessible.
- No ready inventory of equipment was available.

The resulting processes are quite informal and dependent on knowledge gathered by experienced staff members about the facilities operations over the years. As a result, the hospital ends up spending considerable resources on Facilities Management but does not get the results it needs. The BIM-enabled process for recording and delivering as-built information offered an opportunity to record and

provide accurate as-built information, in a form, which helps maintain and manage the facilities in an efficient way and increase the lifecycle of the building.

3.4.2 Effectiveness of ICT in Construction

The earlier view taken regarding ICT implementation was a very simple one, that simply implementing ICT solutions will bring significant improvements on its own. No significance was given to integration of people and process issues, resulting in less than satisfactory outcomes (Dave et al., 2008). Limitations of this approach were soon realised and efforts were put into integrating process issues along with ICT implementation. Business process reengineering/redesign (BPR) initiatives advocate the importance of integration process with information systems. However, BPR became more of a buzzword and focus shifted to reorganising the workforce and processes rather than integrating information systems with people and processes. Socio-technical approaches have tried to address the challenge of integrating people issues with information systems. However, this approach lacks the much-needed focus on process. It can be concluded that prior views on integrating the three core elements of business have been of limited effectiveness as they have only partially addressed the problem.

Koskela and Kazi (2003) have discussed the effectiveness of ICT within the construction sector. They have reported that although ICT has improved productivity on a general level as far as individual tasks are concerned, productivity of the industry on the whole has not benefited. Specifically the site and project management activities have not been addressed properly by the ICT implementations. A number of studies in impacts of ICT in construction are cited where the findings have indicated that even if high levels of benefit from ICT systems are found in design and administration type of work, site management and other construction related activities have remained virtually unaffected. And in certain cases of subcontractors and clients, the impact has indeed been negative. An even more worrying trend is reported by the authors, which states that increased spend in IT has resulted in decreased productivity and safety standards.

At the core of construction there are physical processes, which are supported by information flows among others. Generally, most ICT projects in construction aim

to improve these supporting information flows and hope that this will improve the whole process. However, if the actual production process is as chaotic as construction the implementation of ICT will not bring desired results, if not make it even worse.

This view is supported by a survey carried out by McKinsey and London School of Economics (Appel et al., 2004) where productivity trends of around 100 companies across France, Germany, UK and the United States were surveyed in a period from 1994-2002. The survey showed that investing solely in ICT offerings has a very little impact on company's performance unless accompanied by operational change; and that regardless of the company's size, location, sector or past performance, better management practices improve organisational productivity. This is reflected in the results where lean manufacturing and better people management practices such as performance management and talent management coupled with ICT implementation brings 20% productivity increase, whereas isolated implementation of ICT brings only 2% productivity increase and management practices result in 8% increase. The survey rated the companies from 0-5 in how they utilised the three important tools, Figure 8 shows the results from the survey.

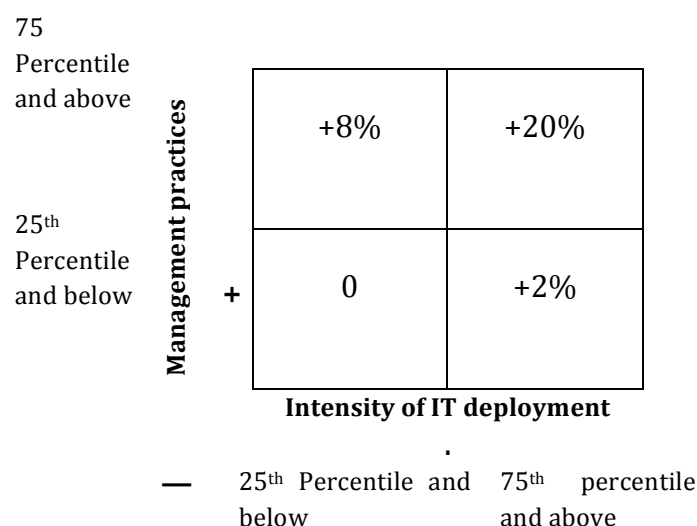


Figure 8. Percentage increase in total factor productivity (Appel et al., 2004).

3.4.3 Problems with Integration in Information Systems:

Researchers have also widely discussed the problem of disparate systems within the construction firms, which results in so called "islands of information" (Bowden

et al. 2006). Various departments across the construction team use their own software systems, which results in duplication of efforts and less efficient processes. This problem of lack of interoperability is widely known in the industry as one of the core issues affecting use of Information Systems within the construction industry. This coupled with fragmented nature of construction supply chain adds to the problem of information integration across the industry (Alshawih and Ingirige, 2003).

The earlier consensus amongst researchers has been that implementing enterprise resource planning (ERP) systems results in a well-integrated system, which will reduce duplication of work and increase efficiency in general. However, in a study carried out by Tatari et al. (2007) in the current state of construction enterprise information systems (CEIS), findings, which are contrary to this belief, are reported. As shown in Table 4, the survey has shown that only 16% of participants were satisfied with their current level of integration from their CEIS implementation where only 4% actually achieved full integration between systems.

Table 4. Level of functional integration within the construction industry (Tatari et al., 2007).

Level of integration	Percent
Full integration with other parties (all functions and many different entities are integrated with seamless real-time integration)	1.3
Full integration (all functions integrated with seamless real-time integration)	12.7
Partial seamless integration (several functions integrated with seamless real-time integration)	32.9
Partial relayed integration (several functions computerized and consolidated in certain periods (e.g. daily, weekly and monthly))	32.9
No integration (several standalone computer applications with no integration)	17.7
No informational system (manual business processes and operation)	2.5
Total	100

In similar research, Rettig (2007) has pointed out that even if businesses aim to radically transform their processes through high investment ERP implementation projects to achieve significant efficiency gain, very few actually go on to realise these benefits. In reality the companies who start with a vision of integrated system where all elements of business processes are streamlined, end up with a patchwork of systems where a large number of software programmes are installed

over the years. As a consequence, companies end up spending enormous amounts of money behind their IT investment, which in fact take them towards rigidity rather than innovative, efficient and responsive business processes. In a study carried out at MIT (Massachusetts Institute of Technology) (Ross, et.al, 2006) where 400 companies were studied, it was reported that IT departments are seen as cost sinks and liabilities rather than centres for innovation.

In contrast, Liker (2003) has pointed out that Toyota in the automobile sector has remained flexible (in comparison with its competitors) by selecting only those information and communication (ICT) opportunities that were needed and which could reinforce the business processes directly, and by making sure by testing that they were an appropriate “fit” to the organisational infrastructure (people, process and other ICT). Shelbourn et al. (2007) have discussed that to leverage maximum potential from ICT projects there must be harmonisation of these three key strategies. In a survey carried out by the authors on the importance of 3 key strategies for effective collaboration, 40% respondents attributed importance to people, 34% to business processes and 26% to technology as shown in Figure 9. The findings reinforce a similar view presented by Wilkinson (2005), that any technology implementation in construction industry should be split; 40% people, 40% process and 20% technology.

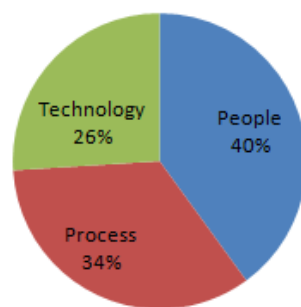


Figure 9. Importance of three key strategies in projects (Shelbourn et al., 2007).

3.4.4 Summary of ICT Problems in Construction:

It can be seen from the discussion that the efforts in the last 2-3 decades to implement technological innovation have not brought satisfactory results for the construction industry. Much has been done to improve processes, which are peripheral, by imitating other industries, but efforts to improve the core

construction processes have not been made. Also, the people aspect (organisational structure and addressing user requirements) has not been addressed. The capabilities in the construction sector are still quite varying.

Specifically from the production management perspective the ICT systems are expected to address the core production process and also product visualisation side-by-side. However, none of the mainstream systems can address the needs of the dynamic nature of production on construction projects.

3.5 Synchronisation, Visualisation and Integration

From the production management viewpoint, the aspects of Information Integration, Visualisation and Synchronisation emerge as the most important factors from the study of previous research and literature, and direct observation. It also emerges that although these are understood to be some of the most important aspects, the current production management systems do not effectively tackle them. Whereas some of the existing systems address these aspects separately, there is a general lack of a system that would have all three features in a single system. For example, it could be argued that a Building Information Modelling system such as Autodesk Navisworks, Tekla Structures (Construction Management), etc. provide a visualisation platform in form of a 4D model (i.e. integration of the Master plan with the BIM model), yet it does not synchronise the production planning and control information (i.e. current information about the production status or detailed planning), and it does not integrate with other information sources such as procurement or resource management system. Similarly a lean production management system such as LEWIS (Sriprasert and Dawood, 2003) does not integrate directly with a BIM model or synchronise information in real-time.

All three aspects of visualisation, integration, and synchronisation have to be taken also from product and process viewpoints, i.e. it is about synchronisation, visualisation and integration of product and process information when designing a production management system.

3.6 Summary

In general, a two-fold problem emerges from analysis of past literature in the area of production management in construction. First is that the production management system itself has problems in construction industry, where the “T” view has been prominent. The “T” view leads to waste not only during the construction phase but also through the whole construction project life cycle. Other factors such as fragmented supply chain, inefficient planning and control system and high variability in productivity rates all seem to stem from this very fundamental problem, which can also be linked to the lack of effective theory behind construction management.

On the other hand, despite the recent advances in ICT systems and a considerable increase in ICT spend within the construction industry, the results are not yet favourable. In fact in some instances the productivity levels have dropped due to inefficient or ineffective implementation of ICT systems. The main problem behind this can also be linked to the predominance of “T” view while implementing or designing ICT systems for construction, as they tend to support the optimisation goals of individual processes and functions rather than the production system as a whole. This has led to problems related to three distinct aspects of information management in construction, namely those of integration, synchronisation and visualisation. It is found that all these three aspects are important from lean production management perspective, but current information systems being used in construction do not adequately support them.

It was also observed in this Chapter that the current product modelling systems such as 2D (and up to some extent 3D) CAD are not capable to efficiently communicate the requirements of today’s complex projects and introduce significant inefficiencies in the process.

These views from literature are supported by the direct observation made by the author while working within the construction industry. In two cases reported, distinct problems related with “islands of information” or non- integrated information systems were found. And despite significant investments in ICT systems to overcome these problems, they failed to address the predominant

problems faced by the companies, especially in the area of production management. Project performances still remained relatively un-affected after the implementation of major ICT systems, as these new systems did not address the core construction processes.

Hence it can be deduced that in order to solve these problems related to production management, any new system would have to address the product and process management in an integrated fashion. Any new approach needs to take care of the “flow” and “value” generation aspect alongside the “transformation” aspect. And most importantly, the newly designed production management system should also address the aspects of information integration, synchronisation and visualisation simultaneously.

Overall, it can be mentioned that the industry needs a capable production management and control system, which also takes into account the spatial nature of the construction process and which addresses all three - “TFV” elements of the production system.

4 Lean Construction and Building Information Modelling: potential solutions to the problems

In constructive research, the next step after the identification of a practically relevant problem is in depth familiarisation with the research area. This is the first step towards developing a solution to the previously identified problem. Following the exploration of problems in Chapter 3, it emerged that the industry needs a capable production management and control system, which also takes into account the spatial nature of the construction process, especially from the context of visualisation and which addresses all three - “TFV” elements of the production system. This Chapter provides an in-depth summary of potential solutions that help achieve these goals.

To begin with, Lean Construction as a potential solution towards production management problems is explored. Here, the TFV theory of production, effects of the “T” view and “making do” as waste in the construction are explained, which is followed by the practical solutions offered by the Last Planner™ system of production control and Visual Management techniques.

Following the discussion on Lean Construction and the Last Planner system, Building Information Modelling as a potential solution to product visualisation and the opportunity to integrate it with Lean Production systems to achieve integrated visualisation of product and process during production management is explored. This then leads to the development of a potential solution through an integrated production management approach.

4.1 What is Lean Construction

Lean Construction can be defined as a set of new processes which are grounded on a new theory of production and which help improve the efficiency of construction by providing better value to the client and reducing waste from the process. This section explores the theoretical foundations and the tools and techniques associated with lean construction that specifically addresses the production management in construction.

4.1.1 TFC theory of Construction:

Koskela (2000) argues that there are three aspects to a production system, namely transformation, flow and value, or in short T, F and V, and all three are critical for efficient functioning of any production management system. Before going further into the TFC theory and how it works, it is critical to understand the effects of relying solely on the “T” view for production.

4.1.1.1 Transformation

The “T” view of production has remained dominant during the whole 20th century in all major industries including manufacturing, automotive and construction barring a few exceptions such as Toyota. In the “T” view, production is mainly managed by breaking the whole project into parts or work assignments called tasks. These tasks are then assigned to workers or teams and are managed relatively independent of each other. From economic perspective, to lower the production costs, the costs are optimized at the task level, i.e. cost of each task is minimized to reduce the cost of the whole product. Koskela et al. (2002) argue that the “T” view has two main deficiencies:

- i. It fails to recognise other phenomena in production other than “T” (such as “Flow” and “Value”)
- ii. It fails to recognise that it is not the “T” itself that makes the output valuable, but instead there is value in having the output conform to the customer’s requirements.

This is not to say that the “T” view is not needed, quite the opposite. It is a fundamental view to identify what tasks are needed to realise production, however it does not help understand how to minimise wastage and improve or realise production value.

4.1.1.2 Flow

There have been other recommendations on production management such as that by Gilbreth and Gilbreth (1922) who first suggested the idea of production as flow. This view led to the “production line” concept that was pioneered by Henry Ford and transpired into “Just in Time” view of production eventually leading to the idea of lean production.

However, Henry Ford's production line idea was mainly misunderstood, until it was redeveloped by Taichi Ohno at Toyota in 1940s and onwards. The flow view is at the core of lean philosophy and it emphasises that there should be a continuous drive to eliminate waste from all flow processes. Tools such as Value Stream Mapping, Lead Time Reduction, Just in Time and Variability Reduction all support the flow view of production.

4.1.1.3 Value

One of the more difficult views to understand and much less explored is the "value" view of production. Here the core premise of production is value generation for customer. Developed or articulated in the 1930s where it was initiated by Shewhart (1931), the value phenomenon was brought to the forefront again by the quality movement mainly in the manufacturing sector.

4.1.1.4 Summary

TFV: Koskela (2000) argues that rather than being competitive or contradictory, these views are in-fact complementary. In the absence of a theory for production, Koskela (2000) puts forward a combined "TFV" theory of production, which takes a holistic view of production from all three viewpoints. An overview of this "TFV" theory as opposed to individual counterparts is provided in Table 5 below. As it can be observed, the individual doctrines and principles representing each of the viewpoints are not new at all, but when combined they provide a perspective and guidelines to help model, structure, control and improve production (Koskela et al., 2002).

Table 5. The TFV Theory of Production (Koskela, 2000).

Aspect of Production	Transformation View	Flow View	Value Generation View
Conceptualisation of production	As a transformation of inputs into outputs	As a flow of material, composed of transformation, inspection, moving and waiting	As a process where value for the customer is created through fulfilment of his/her requirements
Main Principle	Getting production realised efficiently	Elimination of waste (non-value adding activities)	Elimination of value loss (achieved value in relation to best possible value)
Methods and practices	Work breakdown structure, MRP, organisational responsibility chart	Continuous flow, pull production control, continuous improvement	Methods for requirement capture, quality function deployment
Practical contribution	Taking care of what has to be done	Making sure that unnecessary things are done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name of practical application	Task management	Flow management	Value management

4.1.2 Concept of Waste

Koskela et al. (2012) provide a brief history of the concept of waste in production, and emphasise the importance to understand it within the context of production. The authors mention that although it is a foundational notion for the Toyota Production System and in general the concept of lean, it is not recognised well in the theory of economics, operations management, construction management or management in general. The authors found through their research that the up to the end of the 18th century there was little if any recognition of waste, and it only emerged in the 19th century and flourished during the emergence of scientific management. However it declined starting from the second quarter of the 20th century, and re-emerged in the last quarter of the 20th century with the Toyota Production Management System.

Liker (2004) mention that, the elimination of waste is at the heart of the Toyota Production System, and this along with the concept of continuous flow and improvement, were how Taiichi Ohno made Toyota a very efficient car manufacturer. Ohno, who strived to drive out waste from the end-to-end process rather than optimising individual functions, considered following 7 as main wastes within the production system (Liker 2004):

- Overproduction: Any items produced, which are not ordered by the customer, are considered overproduction. Overproduction causes excess

stock, and inventory, and may lead to other waste such as unnecessary transport or rework. In construction, any work that is carried out “outside the schedule”, i.e. was not planned in advance, can be considered overproduction.

- **Waiting (time on hand):** Production workers having to wait to carry out the next planned activity is considered waiting time or waste. Also, time spent in watching automated equipment (such as concrete mixers) is also considered waste. Reasons for waiting time could be lack of inventory, equipment downtime, resource unavailability etc.
- **Unnecessary transport or conveyance:** Any movement of workers associated with transporting material or equipment, “in process” work, or finished parts etc. long distance is considered waste. In construction, this could mean transport of precast elements, or concrete, movement of workers. The reason for this could be lack of attention given to site design, bottlenecks on worker movement routes, etc.
- **Overprocessing or incorrect processing:** Any unnecessary steps or action taken to carry out work can be considered overprocessing. Also, producing work that is of higher quality than required/ordered is also considered overprocessing.
- **Excess inventory:** One of the most important waste considered by Ohno is excess inventory. Finished parts which are produced out of turn (unplanned) and waiting to be processed further are also considered excess inventory. Excess inventory causes problems such as bottlenecks in processing, reduced safety, defects, etc.
- **Unnecessary movements:** Unnecessary motion, including having to search for information, looking for resources, etc. is considered unnecessary movement.
- **Defects:** Work that is completed but is defective or requires rework is considered defects.

All the above wastes exist in construction, however, Koskela (2004) introduces another category of waste in construction called “making do”, which is discussed below.

4.1.2.1 Making do

When one puts this new point in front of the existing construction practices, many shortcomings arising from the sole “T” implementation start becoming obvious. Crucially, this leads to a new category of waste called “Making Do” (Koskela, 2004).

Making-do as a waste refers to a situation where a task is started without all its standard inputs, or the execution of the task is continued although the availability of at least one standard input has ceased. The term input refers not only to materials, but to all other inputs such as machinery, tools, personnel, external conditions, instructions etc. Especially in production situations where there are several uncertain inflows to the task (such as construction), making do is a common phenomenon, and requires explicit attention (Koskela, 2004).

Conceptually, making-do is opposite of buffering. In buffering, materials are waiting to be processed, whereas in making-do the waiting time of one of the material or input is actually negative, i.e. processing starts before the material has arrived. Here, it is important to understand that buffering (high inventory) and making-do are both wastes and as such are utilised to accommodate for the variability in production. Making-do is applied especially in circumstances where there is a demand to speed up production to meet deadlines.

As such making do comprises of and leads to several other wastes such as overproduction, movement, defects, etc. However, in construction “making-do” manifests itself into a significant phenomenon due to the peculiarities of the construction industry (Koskela, 2004).

Transformation View is the main reason for Making-Do: As discussed previously in Chapter 2, the CPM method of production planning and control is solely based on the “T” view of production. In CPM, a plan consists mainly of a Gantt chart and an activity diagram. In the CPM method, each task starts when the master schedule indicates and when the preceding activity has completed. However, it fails to take into account the current situation on site and also the other flows (or prerequisites) to a task. However, as main focus of production is on the realisation of tasks, little attention has been paid to who, when, where, what and how of the flow activities (i.e. making the inputs available to workers). To deal with this

situation on ground, the workers on site tend to find “work around” when the necessary prerequisites are not available, resulting in “making do”.

4.1.3 Effect of the “T” view on Organisational Processes and Technology

Not only does the predominant Transformation view have an impact from the production management perspective, it has also affected other supporting/enabling processes within the construction industry. For example, the problem of “islands of automation”, which means having disparate systems within an organisation or a project that do not interact/communicate well with each other and do not support integration is discussed. It can be asserted that this due to the predominant reliance on the “Transformation” view of production. Instead of addressing the production process as a whole and also catering for the “flow” and “value” aspect the ICT systems, organisational processes and organisational structures (people) support optimising individual processes and neglect the overall production management efficiency. The TFV perspective on Processes, People and Technology is shown in Table 6.

Table 6. The TFV perspectives on People, Process and ICT in Construction (Dave et al., 2008).

	Process	People	ICT
T	Task based approach, leading to fragmented processes. Individual optimisation at each function.	Vertical or “silo” type organisation consisting of isolated functional departments	Leads to the view that ICT on its own brings benefits. “islands of automation” with virtually no or very little integration
F	End-to-end processes, emphasis on waste reduction, time compression, flexibility, transparency	Horizontal or team based organisation.	ICT increases transparency but adds to variability. ERP type approach to integration. Focus on making production information available at the “coal face”.
V	In addition to F processes focus on customer and value	Same as F, but organisations have direct focus on customers	Focus on requirements capture software, supporting requirements and information flow through the project.

4.2 Tools and techniques that support the TFV theory of production

At the root level, the application of TFV theory should eliminate the possibility of making-do, where the flow aspects are taken into account when designing the production system (Koskela, 2000). By focussing on the flow aspects, the attention is towards waste elimination and the causes of waste (i.e. variability etc.).

Koskela and Howell (2002) also ask for an overhaul of the theory of management. According to the authors the approach of management-as-organising as a theory of planning allows the pull type of production control, which is instrumental for ensuring the availability of all task inputs. Also, the language/action perspective, as a theory of execution, focuses attention to commitment towards the plan and to confirmation of the task outcome.

At the practical level, the Last Planner System™ satisfies most requirements posed by the above-mentioned alternative theories, such as management-as-organising, focusing on flow and language/action perspective, and above all a “pull” based production management system.

4.2.1 The Last Planner System™ of Production Planning and Control

The Last Planner System™ or LPS for short is a method of production planning and control on construction sites that has been developed by Ballard since 1992 in the USA (Ballard, 2000). The Last Planner™ system has been successfully used in many countries and has contributed to efficiency improvements and waste reduction amongst other benefits.

The main goal of the LPS is to ensure, through different procedures and tools, that all the preconditions of a task are satisfied when it is started, that the task can be executed without disturbances, and that it is completed according to the plan. The share of tasks completed as planned called “Percentage Plan Complete” or PPC for short is monitored on a weekly basis. The reasons for non-completion are then investigated also on a weekly basis. By influencing the reasons found, an increase of the degree of realization of weekly plans is sought. One further element of the Last Planner method is rolling look-ahead planning, in which the preconditions for tasks are made ready for the next 4-6 weeks. The goal is to maintain a sufficient backlog of ready tasks (Koskenvesa and Koskela, 2005)

There are three additional functions of the Last Planner system:

- i. Get the input (knowledge) from all stakeholders of construction project to plan
- ii. Get commitment from the stakeholders to the plan and to each other

iii. Increased cooperation due to collaborative planning

Koskenvesa and Koskela (2005) provide an explanation of the Last Planner System. The observations on productivity of a construction task by Jaafari (1984) are provided: “the general pattern of productivity of a construction task shows a gradual build up at the start (not remaining sharp as anticipated, due to unavailability of needed inputs). The productivity then steadily rises unless there are external interruptions. Then there is a general unexplained lag/drag at the end (10-15% unfinished task) for a variety of reasons such as crew needed elsewhere, technical problems, etc.”

However, the above observation does not corroborate with the CPM method of planning and control. As shown in Figure 10, in the CPM method of scheduling, the tasks are represented as rectangular bars. It is assumed that there will be sharp start to the task, uniform productivity and a sharp end with no tails or lags. In most cases however, the reality is closer to Figure 11, where there is a gradual rise to productivity in the beginning reaching higher than planned (to meet the delay at start), interruptions in the middle and typically a tail end towards the end.

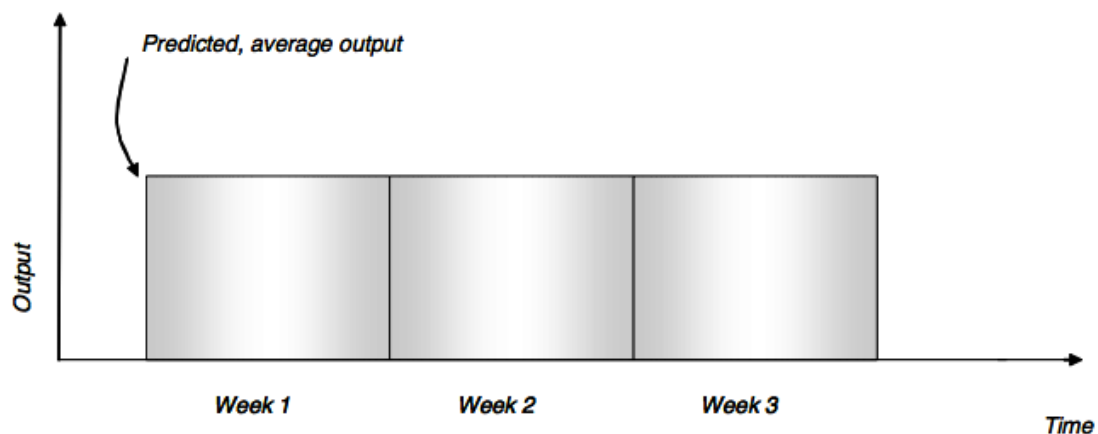


Figure 10. Task productivity as in CPM method (Koskenvesa and Koskela, 2005).

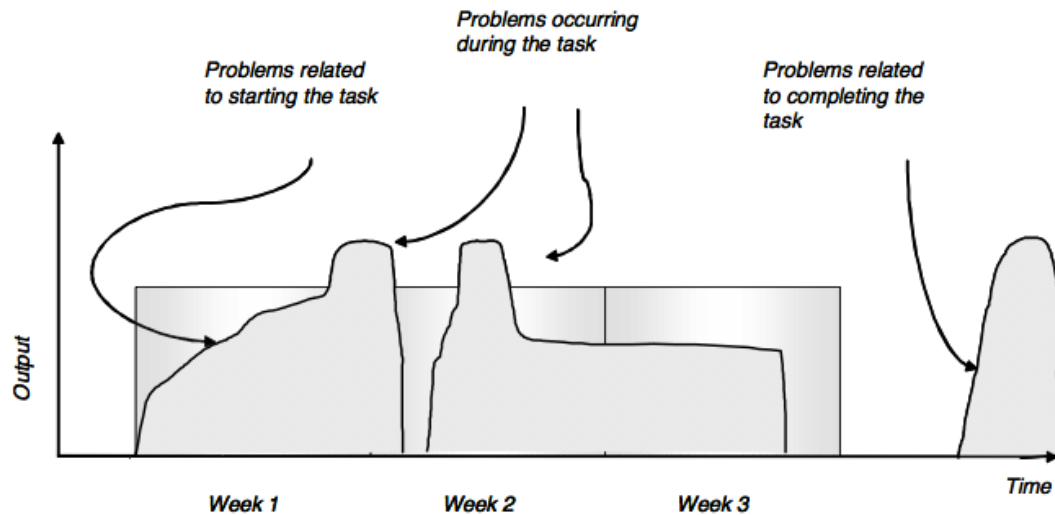


Figure 11. Task productivity of a construction task in reality (Koskenvesa and Koskela, 2005).

The Last Planner™ system is explained in a simple way that it tries to recreate the neat and sharp task representation that can be seen in Figure 10 above, a task starting sharply, reaching the sustainable and stable output level immediately and a uniform productivity rate till the end, finishing the task as planned.

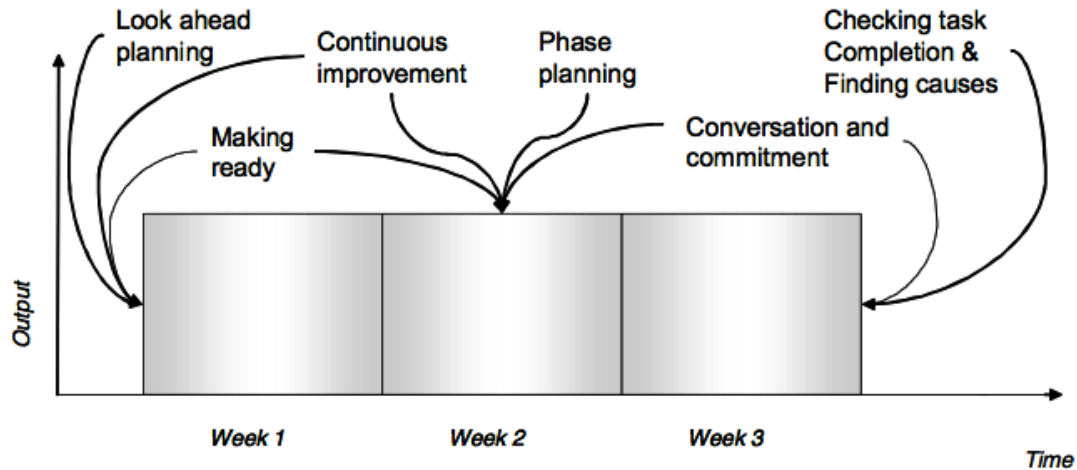


Figure 12. Feature of the Last Planner System in addressing the task productivity (Koskenvesa and Koskela, 2005).

Koskenvesa and Koskela (2005) argue that there are seven features of the Last Planner System that play a role in addressing the task productivity as shown in Figure 12. The following provides a detailed explanation of the Last Planner System and its key features, which partially addresses some of the issues raised above.

4.2.2 Key features of the Last Planner System

This section has largely been adapted from the original text available in “Lean Construction Tools and Techniques”, (Ballard et al. 2002). In production management, planning is followed by control. In traditional construction this is mostly a top-down approach where the head-office or the project managers dictate (control) what needs to be done on the site. Whereas on lean projects, with the use of Last Planner System, the site team which is in charge of actually carrying out the work, takes part in the planning process ensuring that it is more closer to the ground situation. The word Last Planner refers to the Foreman, Site Manager, Shop Foreman, or a line manager, who is in charge of short-term tasks.

- Lookahead Planning
- Weekly Planning (also known as collaborative or commitment planning)
- Continuous Learning (from the PPC and reasons for non-completion)

The main rules of production control with Last Planner are (Ballard et al., 2002):

- Drop activities from the phase schedule into a 6-week (typical) look-ahead window, screen for constraints, and advance only if constraints can be removed in time
- Try to make only quality assignments – require that defective assignments be rejected
- Track the percentage of assignments completed each plan period (PPC or ‘per cent plan complete’) and act on reasons for plan failure.

Ballard (2000) provides a workflow of the Last Planner System as shown in Figure 13.

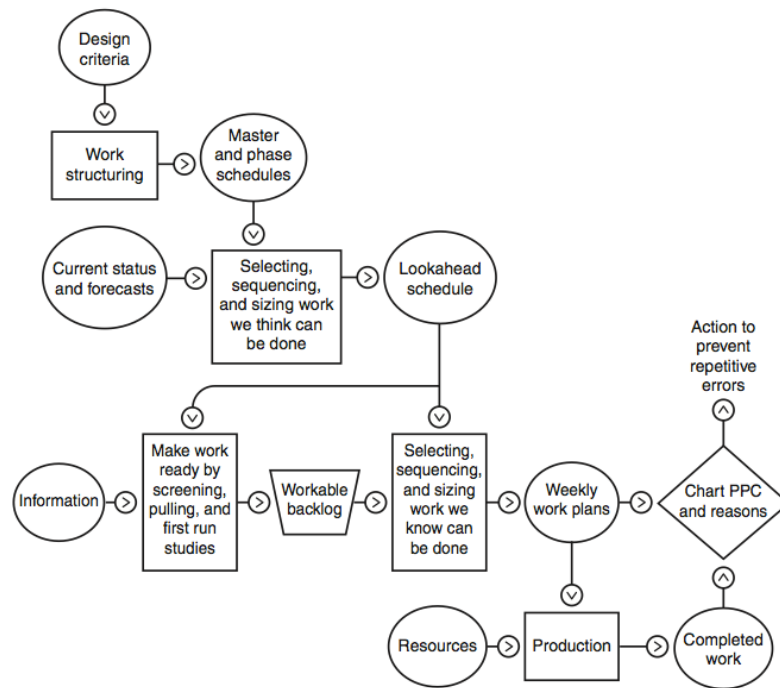


Figure 13. The Last Planner System of Production Management and Control (Ballard, 2000).

4.2.2.1 Look-ahead Planning

Look-ahead planning ensures that there is a sufficient number of mature tasks available to be performed each week. These are the tasks where all the constraints have been removed (i.e. preconditions are satisfied). Typically Look-ahead planning refers to planning carried out 4-6 weeks in advance. Look-ahead planning serves the following key functions:

1. Shape the workflow sequence and rate
2. Match workflow and capacity
3. Maintain a backlog of ready work (workable backlog)
4. Develop detailed plan of how work is to be done (operations designs)

The key tools and techniques involved in Look-ahead planning are:

1. Constraints analysis
2. Activity definition model
3. First run studies

Constraints Analysis: The main focus of the look ahead planning is to consider tasks 4-6 weeks in advance and identify and eliminate constraints. The key rule

here is that no task should be allowed to be in the production schedule if the planners are not sure that all the constraints for that task can be removed in time. This forces the site team to consider the constraints well ahead in time, and ensure only mature tasks for production. Problems such as labour availability or delivery of materials are identified early and dealt with. This reduces variability and improves the smooth flow of production activities. There is a slight danger here of project lagging behind considerably, if constraint removal is not carried out in systematic and diligent manner. For example, if 50 tasks are considered for a particular look ahead window in the master schedule, however in the look ahead plan only 20 are considered due to constraints, the plan reliability may increase locally, however overall project might lag behind. It is up to the project supervisor/manager to ensure that the project does not lag behind significantly.

Also, 4-6 weeks window is an ideal duration for look ahead planning, depending on the nature of the project and organisational processes, this could be between 2-6 weeks. The longer the window, the better the opportunity to control the flow of work. However, extending the window too much in advance makes it harder for the work crew to realistically plan/predict the outcome of constraints removal.

Activity Definition Model: Activity Definition Model (or ADM for short) describes the tasks in further detail following phase planning. It defines tasks associated constraints, work methods, pre-requisite work and resources. Work methods or directives describe how a particular task is to be carried out or assessed. For example, assignments, design criteria and contract specifications. As the name suggests, pre-requisite work are the previous tasks or components, which are required to be completed before a particular task can be started (for example, excavation for foundation, plastering before painting etc.). Resources are simply material, equipment, labour or work conditions. Resources can also have limitations, i.e. working hours for labour, lifting capacity for crane etc.

ADM defines in detail how activity are to be carried out and their relations with each other, and is very useful while carrying out constraints analysis.

First Run Studies: Construction is kind of production where majority of activities are carried out on directly on site – affected by external conditions, as opposed to

manufacturing where production happens in a controlled environment. This makes construction a prototype kind of production. In manufacturing several prototypes are produced before finalising on a single product and also the production method. Whereas in construction, often work begins directly on site without advance consideration of best suitable product options or work methods.

Work methods appear simple enough when represented in the estimate, but that design is seldom detailed or explicit at the step or sub-cycle level. Under lean construction, the design of the product and the process occur at the same time so factors affecting operations are considered from the first. Ultimately, operations design reaches all the way through the delivery system, as it is part of work structuring. There is often more than one way to carry out a particular construction task. On many occasions, decisions made at design/conceptual stage such as material selected or design configuration restricts the choice of work methods. Also, available tools, equipment, labour capacity, and site conditions all affect the chosen work method. The range becomes narrower as the work progresses until the end when the crew decides how to carry out the task in hand.

Hence, there are two possibilities while selecting work methods in construction; one is to leave the options open till the last responsible moment and choose as the operation progresses. Second is to finalise the work method and plan in advance which work methods to use. Choosing either way has their positive and negative factors. On one hand having flexibility till last moment is good but poses problems while planning the work and management of resources and forecasting; on the other hand, finalising the work method in advance provides stability and eases the planning and forecasting, but restricts the work method ignoring developments at site, with a possibility of imposing an inappropriate work method on the site crew. Some of the process design factors are restricted during the design stage, however many operational issues have to be considered during the production stage.

First run studies help the production crew to identify the most suitable process to carry out the task in hand by considering several work methods within the possible range of options. First run studies should be carried out 3-6 weeks ahead of starting a new operation. They are more important for unique tasks where the

site team has inadequate previous experience. First run studies involve performing the operation in hand in as realistic manner as possible, so that process/product issues are identified, resource requirements are known and skills are available while performing the actual operation.

Here, the use of virtual technology can assist the site team by simulating the task on the digital model. With the emergence of Building Information Modelling (BIM) and associated technologies it is now much more feasible to simulate the work in hand beforehand along with visualisation of work process. The main issues to be considered from the point of view of first run studies are (Ballard et al., 2002):

1. Design of the product itself
2. Available technology and equipment
3. Site layout and logistics
4. Size of work packages released to the crews
5. Size of work packages released to downstream crews
6. Potential site environment (temperature, precipitation, wind, etc.)
7. Safety
8. Expected experience and skills of craft workers and supervisors
9. Craft traditions or union work rules

First run studies should not just be carried out for repetitive tasks but all major operations should be considered. First run studies help shape the flow of work and also reduce variability. Once performed and perfected, first run studies help design the optimal process, which eventually leads to standardisation. However, as standardisation in lean construction is not a final frontier, but a step towards continual improvement, the process should be revisited with a view to further improvements (Ballard et al., 2002).

4.2.2.2 Commitment planning (weekly planning)

In the LPS, weekly planning is one of the most important activities, performed collaboratively by the site team, it ensures commitment from all parties. The method defines criteria for making quality assignments (Ballard and Howell, 1994).

The quality criteria proposed are:

- Definition
- Soundness
- Sequence
- Size
- Learning (not, strictly speaking, a criterion for assignments, but rather for the design and functioning of the entire system)

The look-ahead planning process ensures that only those tasks are considered for execution where the constraints have been removed. The weekly planning process ensures commitment from all stakeholders and considers coordination issues. This improves collaboration between stakeholders as they directly communicate with each other and minimises disruption during execution. In the end, arguably the most prevailing waste in construction – “making do” is minimised.

In contrast to the traditional planning process where each construction team (subcontractor) plans their own work, the Last Planner Process requires all subcontractors to attend the collaborative weekly planning session. This ensures that any coordination issues arising during the planning are resolved directly, while also ensuring commitment of each stakeholder directly to the team. This increases trust within the team and ensures smooth running of the project. During the weekly planning sessions, the site team also analyses past week’s performance and measures it in terms of “Percentage Plan Complete” or PPC in short. Reasons for non-completion of tasks are also noted and analysed so that problems can be avoided in future. It is expected that gradually increasing or steady PPC means good productivity levels are being achieved, where as sharp rise or dips in PPC indicate production related problems. Also, increasing PPC not only leads to better performance of the execution team but also for subsequent teams, as they can start work as planned and so on.

The Last Planner considers those quality criteria in advance of committing production units to doing work in order to shield these units from uncertainty. The plan’s success at reliably forecasting what work will get accomplished by the end of the week is measured in terms of the PPC. Root causes for plan failure are then

identified and attacked, so that future problems may be avoided. This is in contrast to the usual “fire-fighting” situation where the site team is always aspiring to reach the production targets set out in the master plan and not performing in optimal conditions.

4.2.2.3 Learning (*reasons analysis and action*)

In LPS, each week last week’s plan is measured and analysed, and reasons for non performance have to be provided by each team. These are then analysed and the root cause of the problem is identified. This helps the site team to learn from mistakes so that they can be avoided in future. There could be various causes for non-completion, i.e. look-ahead plan not accurate, misjudgement by the last planner, late delivery by a supplier, or labour unavailability. In either case improvement must be sought and continual failure in the same category must be escalated and resolved. Carrying out this analysis and improvement activities also improves organisational learning and knowledge management practices. Teams retain knowledge on subsequent projects regarding this process and also common causes for failure leading to better performance.

4.2.3 Visual Management and other lean tools

Lean construction uses a range of tools and techniques to support the production management and other processes. Tools such as KanBan, Andon, 5S are well known and used regularly in lean production. Some of these tools are part of a management technique called Visual Management, use of which is increasing in construction (Tezel, 2011). Visual Management can be defined as a management system that attempts to improve organisational performance through connecting and aligning organisational vision, core values, goals and culture by means of stimuli, which directly address one or more of the five human senses (sight, hearing, feeling, smell and taste) (Liff and Posey, 2004). There are many forms of Visual Management devices or tools that are used routinely, such as notice boards, road signs, safety and other symbols, etc. The main objective of these visual aids is to make communication simple, attractive and efficient (Tezel, 2011). From production management perspective, Visual Management can also be considered as a communication/information strategy that uses visual communication to (Tezel, 2011):

- Increase autonomy (self-management) of the workplace
- Reduce waste, overburden and unevenness
- Increase transparency and pervasive information availability at the workplace
- Remove blockages of information

There are a number of Visual Management functions that help service production management in construction (Tezel, 2011), including:

- Visual order
- Visual standards
- Visual measures
- Visual controls
- Visual guarantees

Some examples of these functions are provided in Table 7. As can be seen from the examples, the “Visual Order” function supports the work place organisation method 5S (Tezel, 2011). The 5Ss are

- Seiri – Get rid of anything unnecessary
- Seiso – Standardising identification and location of work place elements
- Seiketsu – Systemic learning
- Shiketsu – distributing responsibilities for the above 3S
- Shitsuke – training and educating employees and giving importance to safety

The Visual Standard can be in form of posters showing common work methods in form of easy to understand graphics (using cartoon characters as can be seen in the examples), process diagrams or announcements. The main function is to communicate the process requirements to achieve desired behaviour from workers. In construction, these can be posters regarding worker safety, or common work processes being explained in form of a flow chart etc.

The Visual Measures promote transparency of information by being open to everyone and easy to understand. However, at the same time they try to avoid information overload. One of the examples in lean construction is a PPC


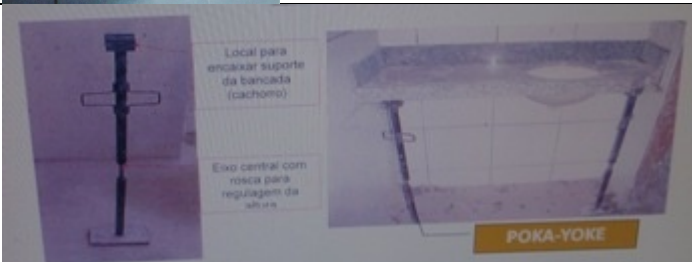
(percentage plan complete) measure of last planner or the pie chart depicting reasons for non-completion. In the examples, the second photograph shows individual PPC of the subcontractors.

The Visual Controls are one of the most important functions of Visual Management, and they help control the aspects of production in a highly effective and visual way. The first example in Table 7 shows a visual KanBan, which helps workers visually identify the level of stock available and when to order new material. The second example shows a Heijunka box, which is used to control production rates of equipment such as concrete mixers. The workers use the Heijunka box to indicate the type of concrete mix, quantity and the time at which it is required by placing a card in the appropriate slot the day before. The mixer operator then uses the cards to plan concrete production and places the cards in the bucket so that transporting workers can easily identify where to take the concrete. The third example shows an “Andon” board, which shows the status of production at any given point in time at various locations on site. The locations to be monitored include buttons to indicate the current status of production, and are colour coded (green, amber and red), while the Andon board is placed in the site manager’s cabin. If the workers anticipate a problem, they press the yellow button, which changes the light for that location on the Andon board. This helps the site manager (or foreman) to respond to the problem quickly. If the work is stopped the red button is pressed, indicating the urgency of the problem. The Andon boards also support the lean concept of worker empowerment, by giving them partial control of the production process.

Finally, the Visual Guarantees are meant to “mistake proof” a function, by guaranteeing the desired outcome through a simple physical or electrical redesign of the process, and is a least developed area of Visual Management in construction (Tezel, 2011). The example in Table 7 show the nails being used to prevent the pipe heads from shifting during installation.

Table 7. Examples of Visual Management functions (Tezel, 2011).

Visual Order	   
Visual Standard	   
Visual Measures	 

Visual Controls	
Visual Guarantees	

4.2.4 Summary of Lean Production Management

The construction process has several problems, many of which can be attributed to the predominant “T” view of management in construction, and also a lack of theory behind construction. Lean construction principles address all three “TFV” aspects and have a range of tools and techniques to support the construction process. Application of such lean tools and techniques in construction has brought positive results and is now being followed by a number of construction organisations internationally.

One of the most popular lean construction tool, The Last Planner System™ addresses some of the problems of the production management, which were outlined in Chapter 3. It helps create a collaborative environment and improves flow of the production process, and reduces variability and improving certainty at the same time. In general, tasks can be started and completed as planned due to being free of constraints, and there is an environment of trust between subcontractors due to the element of commitment planning integrated within the

system. The Last Planner System™ serves as a capable entry point into Lean Construction techniques and is being successfully implemented across many projects ever since it was developed (Kemmer et al., 2010; Kalsaas et al., 2009; Salem et al., 2005).

However, it only partially addresses the production management problems, as it does not address the product management aspect of construction. Some of the problems related to product management aspect in construction are addressed by Building Information Modelling, which is discussed in the following section.

4.3 Building Information Modelling

While Lean Construction addresses some of the problems related to process and production management of construction projects, Building Information Modelling (commonly known as BIM) addresses some core problems related to the product modelling, process modelling and product and process visualisation. It also has a potential to act as a central information management platform that could help synchronise and visualise production related information throughout the project. This section describes what is (and is not) BIM, what are its main benefits throughout the construction lifecycle and specifically its potential to address production management goals.

4.3.1 A brief history of BIM

In recent years, BIM has emerged as one of the most important technological platform in the construction industry (Sacks et al., 2010, Eastman et al., 2007). However, its origins can be traced back as far back as 1975 when Eastman wrote an article in the AIA journal about the working prototype “Building Description System”. In the same period (1970s and 1980s) the early commercial systems around the concept started to emerge. The RUCAPS system by GMW computers was developed around this same technology. In a paper, Aish (1986) described now commonly known features such as 3D modelling, Automatic Drawing Generation, intelligent and parametric components and temporal planning of construction processes etc.

The term Building Information Model was first coined by van Nederveen and Tolman (1992). From commercial viewpoint as well, a number of technological

companies have been developing products since mind 1980s that support the BIM functions that are popular today. Hence at least three decades of refinement and development has taken place to reach a stage where the BIM technology is now.

4.3.2 What is BIM

There are many definitions of BIM; Building Information Model, Building Information Modelling and Building Information Management. The BIM handbook (Eastman et al. 2011) defines BIM as “a verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation”. The whole process could also be described as Building Information Modelling and Management, sometimes also abbreviated "BIMM". The result of BIM activity is a “Building Information Model.” BIM software tools are characterized by the ability to compile virtual models of buildings using computer-readable objects that include characteristics and behaviour which enable designing, analysing, and testing of building design and lifecycle properties (Sacks et al. 2004).

In simple terms BIM models (Eastman et al., 2011):

- i. Are accurate virtual representations of the physical world (building or other construction artefact) which can include also information of process, schedule, maintenance etc. (construction project and operation & maintenance)
- ii. Consist of objects (parts of the building/structure) that demonstrate intelligent and parametric behaviour. For example if a door is considered as an object in the model, it can have the following properties
 - a. Material: Wood, glass, metal etc.
 - b. Type of door: Double or single, Internal or external, sliding or hinged
 - c. Connection to other objects: Typically wall
 - d. Other properties: Minimum height/width, opening direction, lock and other hardware, safety/security requirements, fire protection etc.
 - e. Detailed product information: Manufacturer, type, individual ID, etc.

- iii. Can interact with other construction information systems including other BIM systems
- a. For example, estimating system can read the information contained within the model to fully or partly automate the Bill of Quantity extraction resulting in saved time and increased accuracy.
 - b. The procurement system can link to the model to read the scheduling and supplier data for fully or partly automated ordering process
 - c. The Facility management/maintenance system can be linked to the model to provide period maintenance data, manufacturing information and other operational information about the objects within the model.

The above-mentioned characteristics of BIM are largely due to its parametric nature (or the parametric nature of the objects it contains). The concept of the parametric objects is core to BIM technologies and differentiates BIM from traditional 2D or 3D CAD technologies. Parametric objects are defined as (Eastman et al., 2011):

- Consisting of geometric definitions and associated data and rules
- The geometry of the objects is integrated non-redundantly, and allows for no inconsistencies. When an object is shown in 3D, the shape cannot be represented internally redundantly, for example, as multiple 2D views. A plan and elevation of a given object must always be consistent. Dimensions cannot be “fudged”.
- Objects have parametric rules, which automatically modify associated geometries when inserted into a building model or when changes are made to associated objects. For example, a door will fit automatically into a wall, a light switch will automatically locate next to the proper side of the door, a wall will automatically resize itself to butt to a ceiling or roof and so on.
- Objects can be defined at different levels of aggregation, so a wall can be defined as well as its related components. Objects can be defined and managed at any number of hierarchy levels. For example, if the weight of a wall subcomponent changes, the weight of the wall should also change.

- Objects' rules can identify when a particular change violates object feasibility regarding size, manufacturability, and so on.
- Objects have the ability to link to or receive, broadcast, or export sets of attributes, for example, structural materials, acoustic data, energy data, and the like, to other applications and models.

4.3.3 What is not BIM

A number of misconceptions exist about BIM due to its complex and broad nature. For example, in some instances "3D CAD" generated for simple visualisation purposes but without accurate parametric intelligence and information about objects within the model, is misunderstood as BIM. Such three-dimensional (3D) computer-aided drafting (CAD) models that do not consist of objects, including form, function, and behaviour (Tolman, 1999) cannot be considered building information models.

It is also important to understand that BIM is simply not just a technological platform or a tool that is used only by a small group of users on a project. BIM in fact provides "the basis for new construction capabilities and changes in the roles and relationships among a project team. When implemented appropriately, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration." (Eastman et al., 2010) In this sense, BIM is expected to provide the foundation for some of the results that Lean Construction is expected to deliver.

4.4 Benefits of BIM

The benefits of the BIM technologies span the entire building/construction lifecycle starting from the conceptual design/feasibility stage to handover and facility maintenance stage or even up to the decommissioning or demolition of the building. The following section summarises the most common benefits of BIM at various stages of the construction project (Eastman et al., 2011).

4.4.1 Pre-construction/Feasibility Study

At this stage the main goal is to understand whether the desired functions from a building or a structure can be realised within the available budget and time. BIM

provides a platform to visually appraise the spatial requirements and rapidly quantify the cost and time aspects of the project by linking it with the cost data in a parametric way. Specifically the following benefits are realised:

4.4.1.1 Improving programme certainty through spatial analysis

There are tools available to automatically check models against spatial requirements, for example minimum size of a particular type of room, minimum height of a door or distance between the wall an opening (such as a window). By automating such tasks, the quality and speed of design improves greatly.

4.4.1.2 Rapidly consider and explore design alternatives

By linking the parametric BIM model to cost estimating and energy analysis systems, it is possible to rapidly evaluate design alternatives to analyse the performance of the facility from cost, time and performance perspective.

4.4.1.3 Receive early feedback from downstream players through programme simulation

By linking a high level project plan even during the feasibility study/concept development stage and developing a 4D model, a significant amount of variability can be reduced by carrying out a constructability review. Having a 4D simulation done early on a project where new construction or refurbishment is taking place side-by-side an operational building can also help identify the impact of construction activities on building operation.

4.4.2 Design and Detail

4.4.2.1 More accurate early visualisation of design

With earlier 3D (non BIM) technologies where geometric models were created with non-parametric technologies, significant time and effort was required to generate such visualisations and on many occasions they were not accurate. However, with the advent of BIM technologies, it is now possible to visualise design at any stage with accurately reflects what has been designed. This is significant especially at early stages to capture the design intent from client and to communicate to key stakeholders.

4.4.2.2 Automatic propagation of design changes

Design is an iterative process and changes are made constantly, especially when design from various sources have to be synchronised (i.e. structural, architectural, MEP). With BIM, it is now possible to control and link the object properties in a parametric way, and hence changes made to one object/element ensures that all connected objects change their properties in a parametric way.

4.4.2.3 Generating accurate drawings automatically

Even with BIM, it is necessary to generate and distribute 2D drawings at certain stages. However, drawing generation from majority of BIM system is an automatic process and drawings always correspond to the current model ensuring accuracy.

4.4.2.4 Better collaboration between designers

Synchronising design early ensures minimal rework and improved accuracy and quality of design. With BIM it is possible to regularly synchronise design and perform tasks such as clash detection. This ensures that design is error free and any constructability or performance issues are identified early.

4.4.2.5 Linking design to cost estimates

Many design decisions are linked to the cost, and the possibility to generate automatic cost estimates based on the BIM model at any stage during design enables to client to make better informed decision. It can also help during the bidding/tendering stage to provide an accurate bill of quantities to all bidders.

4.4.2.6 Improving Performance of the Facility

BIM enables carrying out sophisticated simulation such as acoustics, energy and lighting during the design stage. Again, this enables the client to make informed decisions and makes sure the facility performs to the requirements. With government imposing stringent guidelines with carbon emissions, it helps achieve those targets and improves sustainability.

4.4.3 Construction

4.4.3.1 Performing clash detection

With BIM it is possible to synchronise design models from all disciplines before construction begins (and also during construction when design is going on in

parallel) to identify any hard (physical) or soft (tolerance) clashes between elements. This ensures that these issues do not delay the construction process and also minimises rework if the clashes are found after construction has taken place.

4.4.3.2 Using 4D/5D for production planning

When a project plan is linked to a BIM model, the combined model is called 4D. When cost and quantity information is linked to such a model the model is called a 5D model. Such 4D and 5D models can help contractors understand how a construction project will look like at any given point in time. This functionality greatly depends on the level of detail the model is based upon and may vary if the temporary structures are not included and if the plan is only at a high level (i.e. a master plan).

4.4.3.3 Prefabrication with BIM

With BIM the geometric data is accurately represented and this enables building components to be sent directly for automated fabrication using numerically controlled machines. Steel fabricated components, precast concrete elements, fenestration and glass fabrication are already manufactured on construction projects using this method. Offsite construction is proven to improve construction quality and is promoted in the UK by the Government.

4.4.3.4 Integrating supporting systems with BIM

Construction is a complex process and many information systems related to supporting activities such as safety, quality, procurement and logistics are used on a typical construction process. All of these systems share a common data model – that of the construction facility. BIM can provide a common platform to facilitate efficient functioning of these systems.

4.4.4 Fit-out and Handover

4.4.4.1 Visual feedback during fit-out operations

During the fit-out operations, a significant number of parallel activities are going on. The fit-out process can become quite complex especially for projects such as hospital buildings where specialist machines have to be installed, linked and tested before handing over the facility to the owner. In such situations, visually keeping a

track of the progress can be quite useful to ensure efficient operation. BIM can be used to provide a visual workflow for tasks such as – arrival, testing, installation and sign-off of equipment and systems for construction projects. Tasks at a different stage in the workflow can be coloured differently in BIM to visually provide a feedback to the project manager.

4.4.4.2 Digital handover with accurate as-built model

With BIM it is possible to use technologies such as laser scanning to first compare the actual construction with design model and then to provide an accurate as-built model of the facility. Laser scanners provide a “point cloud” of the 3D geometry, which can be imported in many popular BIM systems to then develop a surface model that can be overlapped on top of the design model to make comparisons.

Also, during the handover stage it is also possible for the contractor and subcontractors to capture accurate information about the building from operational perspective. For example, information regarding important assets such as manufacturing data, operational and performance data and service related information could be captured for a digital hand-over to the client.

4.4.5 Operation and Maintenance

An accurate as-built model that carries up-to-date information about a facility’s assets and its operational data can be extremely useful to the FM team. This has been demonstrated by the Maryland General Hospital case study (Eastman et al., 2011). When the Facilities Management system is integrated with the Building Information Model, the operatives can refer to hidden objects (behind the structure) and bring up relevant information to reduce time taken to respond to a call.

4.4.6 Summary

BIM can be seen not only as a technology or a set of technological tools, but as a process change that supports the entire lifecycle of the construction project. It provides the basis for new design and construction capabilities and changes in the roles and relationships among a project team. When adopted well, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration. (Eastman et al., 2011).

4.5 The integration of Lean and BIM

4.5.1 Introduction

As discussed separately, lean construction and Building Information Modelling and their respective benefits and capabilities to address the problems of production management in construction, research is emerging, which claims that while integrated, lean construction and BIM provides a robust solution, as they are synergistic in nature (Sacks et al., 2010a).

As it was observed in section 4.2, Lean Construction has three main functions to serve during the construction process:

- i. Minimise physical and process waste occurring as a result of product and process variability
- ii. Improve flow between activities and improve trust and collaboration between parties, and
- iii. Improve the value generation to the client by ensuring the right product gets delivered at the right time

As outlined in section 4.3, some flagship BIM functions used by the industry, also help realise the Lean goals are (Sacks et al., 2010a):

- **Clash Detection:** It is a function of BIM where models from separate disciplines (architectural, structural and MEP) are aligned against each other and are checked for any physical or clearance clashes. Once clashes are found designers can correct the problems and iterate the models until they are clash free. By carrying out this activity virtually, a significant amount of time and money that would otherwise be wasted through rework or delay is saved. This would be nearly impossible to achieve with traditional 2D CAD technologies, where even if drawings are overlaid on each other, they do not always make it easier for the user to identify where the clash would be in a three dimensional space, and there is no method to automate the clash checking.
- **Visualisation of coordinated/synchronised models:** Similar to clash detection, models from separate disciplines are synchronised and

visualised from the early conceptual design stage. This enables the clients and in particular end users to provide their input and for designers to better understand the requirements from the client. This also ensures a much better requirement and design intent flow down through the various stages of the project. This function contributes directly to waste minimisation and value generation principles of lean construction activities. However, it must be understood that for this to happen, early involvement of stakeholders in the project and use of BIM right from the conceptual design stage is a necessity.

- **Use of the BIM model during production:** Collaborative planning is one of the key functions of Lean Construction and is very popular amongst the lean tools on construction projects in the UK. One of the key functions of collaborative planning is to gain a deeper understanding of the planned activities in advance. Also, one of the related activities is “first run studies” where users try different work methods and sequences to identify how a construction task can be best performed and optimised. By using BIM tools such as 4D planning where a 3D model is linked to the project plan and simulated to demonstrate the activities for a selected period, the team gains a much deeper understanding as compared to the use of 2D drawings during planning meetings. Especially on a complex project where there are complicated services being installed, it becomes increasingly difficult for stakeholders to visualise the task at hand and also the sequence of the process. If used appropriately, 4D scheduling can also serve the function of a virtual “first run study”.

On the other hand, lean construction through its focus on collaboration right from the conceptual design stages, and emphasis on experimentation during production, provides a much conducive environment for BIM implementation. This is especially relevant during the initial strategic adoption of a new technology being applied in the project lifecycle.

There are many other examples where lean functions are supported by BIM activities and vice versa. A detailed study was carried out by Sacks et al. (2010a) that found 56 unique interactions between BIM functions and Lean Construction processes. The authors also found empirical evidence of past and on-going

construction projects to support these interactions. Some key aspects that emerged during this study strongly support the notion that Lean Construction and BIM are not only synergistic but that the synergy spans the entire lifecycle of the project and not just design activities. During the study it was found that three lean principles had the most interactions with BIM functions (i.e. they are best supported by BIM)

- i. Reduction of waste by getting the quality right first time (through a better designed product, reducing the product variability, i.e. changes during the later stages of design)
- ii. Improving flow and reducing production uncertainty which eventually leads to
- iii. Reduction in overall construction time

These are the core functions of lean construction, hence it can be deduced that if exploited properly, these two initiatives have right ingredients for a successful project delivery. However, it should also be noted that the discovery of the breadth and depth of interactions between Lean and BIM is of a relatively recent origin, and it is probable that new types of interaction will be found. Table 8 summarises some of these characteristics in various stages of the project.

Table 8. Characteristics of a Lean and BIM Project.

Design & Detail	Construction	Operations and Facilities Management
Collaborative development of design and detailing	Increasing the resolution of planning by linking fine grained plans to BIM (going beyond 4D)	Linking the BIM model with Facilities Management system
Collocation of design team	Collaborative sharing of models during planning meetings	Using the model for Facilities Management and Operations & Maintenance functions
Involvement of downstream stakeholders during design	Sharing models across the whole supply chain for detailed planning, model based estimating, safety planning and carrying out digital first-run-studies (and what-if scenarios)	Keeping the as-maintained model updated to ensure reliability
Using Last Planner™ in design	Updating the models throughout the project to ensure an accurate as-built handover model	
Detailing the models for construction use	Tagging assets during fit out, track progress of fit out visually and capture relevant asset information and link it to the model	

4.5.2 Emerging Trends around Lean and BIM

Although the synergy behind Lean and BIM and its integration on construction projects is a recent phenomenon, the research behind the integration of these two concepts has been on-going in the last decade.

4.5.2.2 Computer Aided Visualisation Tools

In an effort to evaluate the impact of what the authors termed 'Computer Advanced Visualisation Tools' (CAVT), Rischmoller et al. (2006) used a set of lean principles as the theoretical framework. The authors define CAVT as "the collection of all necessary tools which allow for visual representation of the ends and means of AEC/EPC (Architectural, Engineering and Construction/Engineering Procurement and Construction) design and construction project...the CAVT definition also considers underlying information about facility components and activities that might lead to a 3D rendering, a 2D plot, a bill of materials, a work order report, or a virtual reality environment, each coming from a unique product and process model representation, which can be visualized through a computer based display device". The authors' definition of CAVT is very close to what is now known as BIM, and can be considered as such.

The authors placed key emphasis on value generation during the design stage of the construction project. Five key principles covering the value generation cycle in the design process were used as a qualitative framework to analyse the impact of CAVT.

1. Customer requirements captured by the design: Aim to ensure that all customer requirements, both explicit and latent, have been captured by the design.
2. Customer requirements available during the design: Aim to ensure that relevant customer requirements are available in all phases of production and that they are not lost when progressively transformed into design solutions, production plans, and products.
3. Suitable capability of the production system: Aim to ensure the capability of the production system to produce as required.

4. Construction requirements satisfaction: Aim to ensure that requirements and constraints of the construction process have been taken into account during design.
5. Impact of design errors during construction: Aim to minimize the impact of design errors detected during construction.

Based on the case studies conducted over a four year period, it was concluded that application of CAVT results in waste reduction, improved flow and better customer value, indicating a strong synergy between the lean construction principles and CAVT. The authors described the main observations of their comparison between the traditional and CAVT processes when applied on a construction project as shown in Table 9. Overall, qualitative and quantitative improvements were noted in all aspects of the project. Some key observations from the production management perspective are noted below:

Table 9. Comparison of traditional design vs. CAVT (Rischmoller et al., 2006).

Traditional	CAVT
It is a “push” based system where the design is treated as an “end goal” rather than the “mean”. Aspects such as constructability, minimising waste and resource management are not taken in account (or they are not effective).	“Pull” based system where construction requirements drive the production system capability. The capability to visualise design alongside constructability early during the design stage helps minimise waste and manage resources effectively.
Early constructability reviews include design coordination meetings where the output is in form of notes and sketches.	3D design enables early in depth constructability reviews where the input from construction teams is fed back directly in design.
During construction, the approach towards design is reactive, where the teams review already issued 2D drawings to identify changes, based on which design is reviewed and new set of drawings issued.	In CAVT, 4D planning and scheduling helps identify problems in more natural way. Automatic clash detection of model elements helps “sanitise” the design before issuing drawings for construction resulting in less rework.
The deficiencies in design and problems with communication of 2D drawings mean that the Request for Information (RFIs) or Notice of Change (NOC) requests are quite high during the construction stage. These problems also lead to rework and delays during construction ultimately leading to cost and time overrun.	Early involvement of downstream stakeholders helps detect errors early and reduces RFIs and NOCs during construction. Ultimately this leads to increased efficiencies during construction and helping achieve construction within given time and budget.

In Summary, it can be concluded that this early study exploring the link between Lean Construction and BIM (CAVT) reported some very positive findings. It also, highlighted specific benefits from Production Management perspective. The lean context through which the CAVT concept was validated and analysed also provides an interesting perspective, which is further, extended and explored by Sacks et al. (2010) and others and is discussed further in this section.

4.5.2.2 Virtual Design and Construction

In another attempt to integrate lean construction processes with BIM, Khanzode et al. (2006) attempted to provide a conceptual framework to link Virtual Design & Construction (VDC) with the Lean Project Delivery Process (LPDS). VDC has been defined as “the use of multi-disciplinary performance models of design-construction projects, including the Product (i.e., facilities), Work Processes and Organization of the design - construction - operation team in order to support business objectives” (Fischer et al., 2004). The authors claim the “VDC approach allows a practitioner to build a symbolic model of the product, organization and process (P-O-P) early before a large commitment of time or money has been made to the project”. According to the authors, VDC comprises of the following tools and techniques:

- 3D visualisation tools such as Autodesk Revit, Architectural Desktop, etc., i.e. systems that support the creation of a BIM model. The tools that help develop a common understanding of the project and also help coordinate the work of several disciplines. (Clayton et al., 2002)
- Product and process modelling, visualization and simulation tools such as Autodesk Navisworks, CommonPoint Project 4D, etc. These are the systems that support the linkage of the production plan with the model to generate a 4D model. (Koo et al., 2000)
- Organizational and process modelling tools such as VDT and SimVision, i.e. tools that support simulation of the organisational process and identify potential risks. (Christiansen, 2002)
- Online collaboration tools such as project extranet systems and virtual meeting systems that support geographically distributed teams to

collaborate with each other around a central information model. (Shreyer et al., 2002), (Fruchter, 1999)

- Techniques to analyse the effectiveness of multi-stakeholder meetings in order to meet the business objectives of the project and the client. (Bicharra et al., 2003)

As with CAVT, the VDC concept can be taken to represent BIM, or aspects of BIM, due to the similarities in underlying principles and technologies. Here too, results from a case study confirmed that the application of VDC enhances the Lean Project Delivery Process when applied at the correct stages.

The key findings reported by the author through the study are:

- VDC tools such as product, process and organisational modelling tools can be applied very effectively to accomplish Lean Construction goals
- Product modeling tools like 3D modeling can be effectively applied to the Project Definition, Lean Design and Lean Assembly phases of the LPDS.
- Product and process modeling tools like 4D models can be applied during the Lean Supply and Lean Assembly phases of the LPDS.

Gilligan and Kunz (2007) reported that the use of VDC in an earlier project was considered to contribute directly to the implementation of lean construction methods: 'Early interaction between the design and construction teams driven by owner Sutter Health's Lean Construction delivery process used 3D models to capitalize on true value engineering worth nearly \$6M'. Khanzode et al. (2005) provide additional descriptions of the project and the use of VDC and lean methods in its construction.

4.5.2.3 A Pull flow based planning system

Sacks and Barak (2008) discussed the potential contributions of BIM to visualisation of the product and process aspects of construction projects in terms of lean construction principles. They provided examples that illustrate the use of BIM and related technologies to enable a "pull flow" mechanism to reduce variability within the construction process.

4.5.2.4 Integrated Project Delivery

The American Institute of Architects (2007) defines Integrated Project Delivery (IPD) as: “a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction”. IPD provides a suitable platform and project environment for the integration of Lean Construction principles and BIM. Key features of Lean and BIM, such as early contractor involvement, integrated design and the whole lifecycle approach are well supported by IPD. IPD leverages early contributions of knowledge and expertise through utilization of new technologies, allowing all team members to better realize their highest potentials while expanding the value they provide throughout the project lifecycle. However, it is the collaborative structures inherent in an IPD legal agreement, which break down barriers and thus enable these benefits.

IPD (Integrated Project Delivery) and VDC are emerging techniques that leverage BIM to provide an integrated project management and collaboration platform, the first focussing on design and the second on construction. Both are emerging, but they are being developed and their adoption within the industry is increasing rapidly.

4.5.2.5 Further evidence from the field

Eastman et al. (2011) provide ten detailed case studies of BIM implementation, two of which focus on projects in which prefabrication was used extensively. In the context of detailed design for fabrication and delivery by subcontracted suppliers of prefabricated elements, they comment that ‘Lean construction techniques require careful coordination between the general contractor and subs to ensure that work can be performed when the appropriate resources are available onsite. Because BIM provides an accurate model of the design and the material resources require for each segment of the work, it provides the basis for improved planning and scheduling of sub-contractors and helps to ensure just-in-time arrival of people, equipment, and materials.

4.5.3 Summary of recent developments in Lean Construction and BIM

It can be observed from the above discussion on the conceptual developments such as CAVT and VDC and empirical evidence from case studies that both these initiatives (lean construction and BIM) contribute towards an overall efficient construction process. It also emerges that their simultaneous development brings higher benefits than their individual implementation. The early belief that BIM only addresses the design stage in a construction project and is only partially useful during the production stage, is negated as it becomes clear that BIM can be applied through the whole lifecycle of the facility.

The following section provides a summary of the currently available commercial BIM systems for production management.

4.6 Current BIM Systems for Production Management

It is important to identify what are the current systems in the market that support the construction management/production management activities. Also, to avoid duplicating the features available with the current commercial systems, their main limitations and available features should also be identified. These features may include, but are not limited to:

- i. Construction sequencing – known as 4D simulation
- ii. Clash detection – analysing clashes between various designs (such as architectural, structural and MEP)
- iii. Visualisation of design during construction
- iv. Communication, including marking up of design for clarification
- v. Quantity and cost take-off
- vi. Constraints analysis
- vii. Evaluation of what-if scenarios
- viii. Visual tracking of progress

4.6.1 Autodesk Navisworks

Navisworks was originally developed by the Sheffield based developer of same name, but was later acquired by Autodesk in June 2007. Navisworks is predominantly a construction visualisation, clash detection and 4D simulation

platform. It also let's users save animations from visualisation or create snapshots of 3D views that can be rendered and shared with others.

One of the core features of Navisworks is that it can work with all major file types produced by different BIM (and 3D CAD) software. It is well understood that even within a single construction project, BIM models from various applications could be developed. With Navisworks it is possible to synchronise/combine such models and perform the aforementioned functions such as visualisation, clash detection, etc. The other important feature of Navisworks is its ability to handle large files.

Navisworks has two versions:

- A free viewing software called Navisworks Freedom
- Navisworks Manage with full features as discussed next

Some of the key features of Navisworks Manage are described below:

4.6.1.1. Coordination

Coordination, formerly known as Clash Detective, as the name suggests lets the user combine several models (such as Architectural, Structural, Mechanical & Electrical) and check them against physical or clearance clashes. Physical clashes are where various elements collide with each other physically (where this behaviour is not expected), whereas clearance clashes are present when the clearance between two or more objects is less than the minimum specified. The clash detection feature is one of the most useful tools throughout the design and early construction stages where design is still evolving. It lets users identify and resolve clashes which otherwise would have occurred during construction and caused delays.

4.6.1.2 Simulation and Analysis

TimeLiner is a 4D simulation tool which lets users integrate/connect a project plan with the 3D model to simulate the project as it would be developed according to the given schedule. It is possible to import plans from popular programming/scheduling system such as Primavera, Microsoft Project, Asta Teamplan, etc. The new versions of the software also enable linking cost data to the schedules to create what is known as 5D models.

4.6.1.3 Project Viewing

Formerly known as Presenter, NavisWorks provides a set of advanced visualisation tools that lets users navigate an existing BIM model. There are features such as:

- Enabling gravity to provide a more realistic experience where the virtual “avatar” can’t walk through walls, and can climb stairs, etc.
- Flythrough, where quick visualisation without gravity rules is possible
- Several tools that help navigate the model such as ViewCube and SteeringWheel.

4.6.1.4 Project Review

Project review covers the following features:

- Model file and data aggregation: Enables several data source such as laser scans and 2D or 3D models to be combined with the main model
- Review toolkit: Provides tools for measurement from the model (distance, size, etc), storing camera views and cross sections and software automation.
- Model publishing: Enables publishing the model to native and other file formats and also lets users control the security features
- Collaboration toolkit: Users can add mark-ups to models which can be shared with other users for model based communication

4.6.2 Bentley ProjectWise Navigator

Bentley is also one of the platforms that has a wide range of BIM product portfolio. Their product Bentley’s ProjectWise Navigator is used predominantly for collaboration during project and offers construction management features. ProjectWise Navigator has replaced previous Bentley applications – Bentley Explorer, Photo Realism, Bentley Explorer NWD and Interface Detection. ProjectWise supports all major type of BIM, CAD and other geospatial models. The key features of ProjectWise Navigator are described in Table 10.

Table 10. Main features of Bentley Projectwise Navigator.

Viewing and navigation	Analysis and simulation	Reviewing and collaboration
Opening a range of model files including native (Bentley), Autodesk, pdf, etc. and also point cloud data from laser scanners	Detecting physical and clearance clashes	Review and mark up designs with redline comments, managing mark up workflows with mark up dialog
Model visualisation through various modes such as walk, fly, pan, rotate, etc.	Simulating project planning through 4D, linking multiple schedules to the model (for simultaneous review)	Adding simple graphics to enhance “what if” scenarios and assess impact
Filtering, sectioning and slicing the model (loading only selected parts of the model) for simplified viewing	Animating objects based on schedule tasks or construction status (status filtering)	Registering and preserving comments against model items

4.6.3 Synchro

Synchro, based in Birmingham, England started software development in 2001, and offer project production planning, scheduling, resource management and 4D construction simulation software. It is one of the few dedicated BIM software applications that is aimed directly production planning, resource management and scheduling for construction sites. Synchro provides following features:

- Task status control and sequencing options
- Resource management
- Multiple baselines to compare actual performance against the plan
- Progress tracking
- Critical path analysis

Synchro’s resource management includes 3D representation of material, equipment, human and space resources. It also allows cost to be allocated to tasks and resources, which can then be used while reporting for Earned Value Analysis.

Synchro can handle major file formats including DWF, DWG, Bentley, SolidWorks, etc and can also import project plans from software such as Microsoft Project, Primavera and Asta Powerproject. Synchro can also accommodate temporary works and temporary work locations that can be simulated along with main project model.

4.6.4 Vico Constructor 5D

Vico has a specific construction related products suite called Vico Office. In its 3rd product release, it offers following functions:

4.6.4.1 Visualisation

Similar to other construction management tools discussed above, Vico Office can also handle models from most popular authoring tools such as Autodesk, Bentley, Graphisoft, etc. It can also open IFC files. Once imported, it is possible to use different tools to visualise the models using the standard tools such as panning, zooming, rotating.

4.6.4.2 Constructability Analysis

It is possible to carry out clash detection by loading various models such as Architectural, Structural and HVAC in Vico. As Vico's production management features are based on the Line of Balance (Location Based Scheduling) method, it also offers the users the capability to split the model by locations. It is possible for users to define and save comparisons and re-run the comparison (clash detection) when a new model becomes available. It is then possible to issue and manage RFIs from the software. It is also possible for users to annotate models and communicate with other users to clarify design and construction related issues. Users can also use the synchronised models for quantity take-off directly from the software. Quantity take-off can be based on locations to obtain better clarity. A feature of Vico is to develop cost calculations based on recipes, where a recipe is a description of the material, labour and other resources required to complete a task, and is a part of the cost database.

4.6.4.3 Scheduling and Production Control:

As mentioned above, Vico is based on the Line of Balance method of scheduling and has a module called LBS Manager that lets users divide the model by work locations. Once the models are divided, they can be linked to tasks, and subsequently to resources such as material, labour equipment, etc. Based on the linked plan with model, 4D simulation can be generated to develop a 4D plan of the project.

4.6.4.4 Reporting and Analysis

Reports such as constructability (clash detection and mark-ups), quantity take off (overall and by locations), project cost reports, visual budget, flowline (line of balance), and resource histograms can be generated directly from the software. It is also possible to produce a production control chart that can represent a weekly report (tasks completed in a week).

4.6.5 Tekla CM and BIMSight

One of the oldest parametric modelling software, Tekla also provides software capabilities for construction management. Tekla's strength is in its structural modelling capabilities especially in steel structures. However, Tekla can accept models from most other authoring tools and has extensive IFC file handling capabilities. Due to its steel detailing and modelling heritage, it is also one of the software platforms that integrate well with model based prefabrication (where model data can be directly sent to manufacturing machines to automate fabrication of components) using CNC (Computer Numeric Control). Tekla also offers a free software tool called BIMSight, which enables users to import models from all popular authoring tools, visualise them, perform clash detection, review, mark up and measure and also communicate with other team members. Some of the key features provided by Tekla CM and BIMSight are:

- Visualisation and navigation of multiple models (combining multiple discipline models)
- Review and markup of models and sharing with other users
- Automated clash detection
- Communication with other members by creating, sharing notes (and annotations) and online sharing with other members.
- Performing 4D simulation using Tekla CM – by linking project plan with the combined model
- Procurement integration – automated updates in 3D about material movement (material tracking)

4.6.6 Solibri Model Checker

Solibri, a Finnish software company provides a solution called Solibri Model Checker that analyses Building Information Models to check for integrity, quality and physical safety based on the rules defined by the users. The software also lets users combine models from various disciplines, visualise them and perform clash detection for constructability analysis. Solibri is known for its rules based checking engine. Solibri Model Checker offers the following features:

- Import BIM models from all major authoring platforms and also IFC files
- Automated checking and analysis of the building design based on pre-defined rules, highlighting potential problems in 3D and classification of issues based on severity.
- Automated space analysis and measurement
- Automated quantity take off
- Automated clash checking based on components' design discipline and type and severity
- Safety analysis of the model both from construction and also from Facility Management perspective
- 3D visualisation with walk-through and use of gaming controls

4.6.7 Comparison between systems

As it can be seen from the above discussion, all major systems offer the following basic features:

- Visualisation of the combined model to gain better understanding of the design
- Clash detection between different models for constructability analysis
- 4D planning – linking of the project plan (mostly at master plan level) to the model and creating a simulation of the project
- Marking up models and collaborative sharing of mark up

Table 11 provides a comparison between the above-mentioned systems from their construction management capability viewpoint. The above mentioned software systems have features in different ways, their functionality may differ slightly while in use. These tools offer some significant benefit over the traditional CAD systems where construction users have to use imagination to gain a deeper understanding and yet some of the functions such as clash detection or 4D simulation would not be possible to achieve. A wide range of case examples of benefits is emerging from the use of such systems in the industry. On some of the complex projects such as a hospital, multi storey commercial building, stadiums, etc. it is not uncommon to identify several hundred if not thousand clashes during design and early construction stages (Eastman et al., 2011, Kymmell, 2008). If found during construction, these clashes and other constructability issues would cause significant delays and cost overruns to the project outcomes. Hence, it can be concluded that these tools are highly beneficial.

However, in terms of detailed production planning, scheduling and control capabilities, the capability of BIM tools still remains limited. Barring Vico and Synchro, none of the tools offer detailed production planning and resource linkage to the production plans, and mostly offer 4D planning capability which let the users simulate the project only at the master plan level.

Both Synchro and Vico demonstrate some capability to provide a detailed production planning by enabling the development of detailed plans and links to the model. Also, neither Synchro nor Vico offer the “pull” production management capability, however Vico has partially implemented the Lookahead scheduling workflow. Also, Vico is predominantly based on the Line of Balance scheduling method and for projects which are not using this method or the teams which are not familiar with the method, the usability remains somewhat limited.

It was found from the feedback gathered from key users that both Vico and Synchro are of complex nature and prior training and experience is required before the users can start to use them to its full potential. This remains one of the critical issues for software being used for production planning and control. For such a complex system, it may not be possible to train the whole supply chain and

site team in using the system on daily or weekly basis, hence it remains a tool to be used by a selected few users located at the head-office or a central BIM team. This somewhat limits the usability of the system to be used on site.

Also, neither of the system provides detailed constraints analysis at task level or assignment of responsibility and real-time task status updates to enable accurate production planning. As it was observed, one of the cornerstone principles of pull planning is to carry out detailed constraints analysis at the look-ahead and weekly planning level and to assign responsibility to task/trade leaders/managers to ensure the constraints are removed before the tasks are considered for production. However, such level of production planning is not yet available in any of the commercially available systems.

It was also discussed in section 3 that a range of information sources have to be integrated in the production management systems in real-time to enable accurate decision making. Information such as material procurement and delivery, equipment hire and availability, labour availability, space availability, etc. Again, none of the commercial systems mentioned can deal with dynamic integration of such information sources (which could originate from individual information systems such as main contractor's or subcontractors' Enterprise Resource Planning system).

Hence it can be concluded from the above discussion that while the current systems offer a significant improvement compared to the traditional 2D CAD and 3D CAD systems from the production planning and control perspective, there is still potential for improvement and a gap in the current commercial product availability.

Table 11. Comparison between Construction Management Capabilities of BIM Systems.

Features System	Autodesk Navisworks	Synchro	Vico Constructor	Tekla CM	Tekla BIMSight	Solibri
Visualisation of plan and Model	X	X	X	X	X	X
4D Simulation	X	X	X	X		X
Visualisation of temporary works		X	X			
Clash Detection	X	X	X	X	X	X
Resource loading		X				
Constraints Analysis			X			
Visual Task Information						

4.7 State-of-the-art in software systems for production management

The area of production management (planning and control) software systems has been relatively under researched. Most research in the area of BIM (or computer aided design) based visualisation in construction has been focused around pre-construction planning and design stages (Sacks et al., 2009). Apart from one, all other systems discussed here are research systems. However, there have been few notable exceptions, which are discussed in this section.

4.7.1 WorkPlan System

Choo et al. (1999) developed a software system developed at the University of California at Berkeley called “WorkPlan” that helps systematically develop weekly work plans. WorkPlan was based on the Last Planner method of production planning and implementations constraints analysis and other lean principles. The following were the key features of the system:

Planning & Scheduling:

- Spell out work packages
- Identify constraints

- Checking constraint satisfaction
- Releasing work packages &
- Allocating resources

Reporting and Analysis:

- Collecting field progress data
- Reasons for plan failure

The WorkPlan system was developed using Microsoft Access 7.0 database and VBA (Visual Basic Access) as the programming language.

Figure 14 shows the work package entry form. For each work package entered in the system, five constraints are automatically generated by the system by default, namely:

- Contract
- Engineering
- Materials
- Labour and equipment
- Prerequisite work

The screenshot shows a 'Work Package Entry Form' with the following fields and controls:

- WP Code:** A text box containing '110'.
- Project No:** A dropdown menu showing '97-309-C'.
- Description:** A text box containing 'PH Roof-Area A: Metal Deck Installation'.
- Budget:** A text box containing '\$0.00'.
- Input Constraints:** A button located to the right of the Budget field.
- Add Work Package:** A button at the bottom left.
- Delete Work Package:** A button at the bottom center.
- Navigation:** Two arrow buttons (left and right) and a small icon button (possibly for help or search) at the bottom right.

Figure 14. Work Package addition in the WorkPlan system.

Work Package Constraints

Work Package No 97-309-C-110

Work Package Description PH Roof-Area A: Metal Deck Installation

Detailed Constraints

Contract Engineering Material Labor and Equipment Prerequisite Work

Complete (1)

Problem	Solution	Completed
Shop drawings not turned in.	Call A&B	<input checked="" type="checkbox"/>

Incomplete (0)

Problem	Solution	Completed
Submittals not turned in. Submittals unapproved. Shop drawings not turned in. Shop drawings unapproved. Outstanding RFIs Methods and procedures undecided Assembly drawings unreceived		<input type="checkbox"/>

Figure 15. Work Package constraints input screen in WorkPlan.

Any constraints or problems relevant to each of the categories are input by the user and once the resolution is achieved, they are marked as complete, as demonstrated in Figure 15 above.

The system also allowed resource management for work packages by letting the users enter labour and equipment requirement for each work package. These requirements were then compared against the actual usage, and also their cost analysed. From reporting perspective, the system generated a weekly work plan at the Work Package level and also generated the PPC, reason for non-completion and timesheet reports.

WorkPlan was one of the early examples of a Production Management system based on lean methodology. Although it facilitated constraints analysis and look-ahead planning, the system did not go beyond the work package level (i.e. break the work package down to tasks) and assign individual constraints to tasks. Also,

the constraints allocation to responsible actors and communication between workers/task leaders, foreman and project managers was not supported. Also, one of the other crucial aspects that was ignored was the direct engagement of the Last Planners (the construction team). Due to the complexity and the style of the system, it would require a Planner assigned to the project to develop work packages and facilitate the use of the system.

One of the other missing feature was the product information, or visualisation of the project model (such as a BIM model). This is probably due to the fact that BIM was still in its infancy, and CAD systems do not support such kind of integration.

4.7.2 LEWIS

LEWIS, which stands for Lean Enterprise Web-based Information System for Construction, is a research prototype software system developed at the University of Teesside (Sriprasert and Dawood, 2003).

LEWIS supports what the authors describe as multi-constraint planning technique. This technique takes into consideration the following requirements as outlined by Sriprasert and Dawood (2003):

- Collaborative and multi-level planning – This refers to collaborative planning where work crew (Last Planners), project planners and other upstream stakeholders (such as clients) participate in the planning process during project execution.
- Constraints analysis – Consideration and analysis of physical, contract, resource and information constraints, and their evaluation and communication.
- Effective handling of uncertainty – Proactively identifying uncertainties, and compensating by inserting appropriate buffers.
- Visual representation of planning – Visual representation of planning output.
- Practicable optimisation – hybrid optimisation technique comprising of genetic algorithm and heuristic approaches.

Figure 16 provides an overview of the LEWIS workflow.

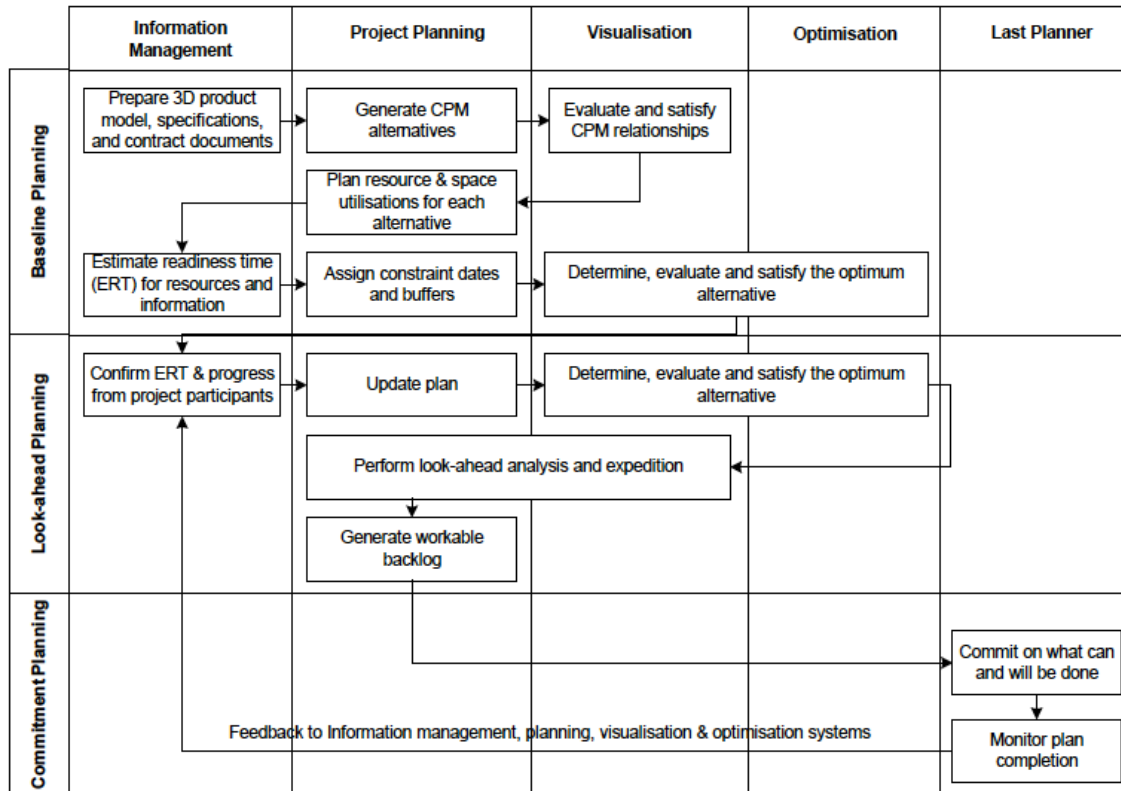


Figure 16. Workflow for the LEWIS system (Sriprasert and Dawood, 2003).

The central idea of LEWIS system is to provide planners accurate information about constraints, which they can consider while developing Look-ahead and Weekly assignments to the production teams at site. The production teams will then retrieve this information, raise queries/questions regarding practical problems, seek resolution where needed and execute the work. LEWIS was developed using SQL server as the database layer, which integrates information from the product model (CAD), process model (schedule), upstream information (specifications, method statements, resources information, etc.) and downstream information (weekly work plan and feedback). The main interface was constructed using HTML (Hyper Text Markup Language), Active Server Pages, VB Script and Java Script. The visualisation interface was developed using VBA (Visual Basic Application) and Autodesk Architectural Desktop 3.3.

The system provided following functions:

- Look-ahead planning: Shown in Figure 17, this module facilitated development of look-ahead plans which was supported by visual

constraints analysis (linked to the 3D product model) and offered automated optimisation based on the constraint statuses.

- Multi Constraint Analysis: This aspect of the system relied on the stakeholders to input relevant constraint related information into the system such as readiness of information, resource, activities (other production activities).
- Constraint, product and process visualisation: Integrated with 3D information using Architectural Desktop 3.3, the system enabled linking tasks and constraints to the product model. It also enabled the visualisation of
 - Space constraints (process clashes)
 - Resource constraints
 - Status of planned and actual work
- Weekly/Commitment planning: Based on the look-ahead plan, the project superintendents were asked to generate a work-plan by adding sub-activities under a constraint free activity.
- Work face instruction – Other work related information such as specifications, work instruction and drawings were linked to the system to enable better facilitation of work
- Feedback – Charting of PPC (Percentage plan complete) and reasons for non-completion was facilitated.

All Constraint Activities Next Month
October, 1999

Uniclass	Task Name	Drawing_No	Drawing_Ready	Method_No	Method_Ready	Material_No	Material_Type	Material_Ready	TaskID
D72111-G21-G21-G311-JE053	Insta path to lecture theatre (for precast)	AS01	False	MS006	False	5	Concrete	False	22
D72111-G21-G21-G311-JR12	Underslab drainage	AS02	False	MS007	False				23
D72111-G21-G21-G311-JF10z1	Substructure brick and block work GL 1-5	AS03	False						24
D72111-G21-G21-G311-JD2-Z1	Hardcore filling and blinding to underside slab GL								26
D72111-G26-F137-G261-G311-JG10z1	2F Column GL K-B/1-5	SC05	True						36
D72111-G26-F137-G261-G311-JG10z2	2F Column GL A-M/6-14	SC06	True						37
D72111-G26-F13601-G262-G311-JG10z1	1F Beam GL K-B/1-5	SBE1	True	MS004	True	4	Steel	False	39
D72111-G26-F13601-G262-G311-JG10z2	1F Beam GL A-M/6-14	SBE2	True	MS004	True	4	Steel	False	40
D72111-G26-F137-G262-G311-JG10z1	2F Beam GL K-B/1-5	SBE3	False	MS004	True	4	Steel	True	42
D72111-G26-F137-G262-G311-JG10z2	2F Beam GL A-M/6-14	SBE4	False	MS004	True	4	Steel	True	43

Figure 17. Example of look-ahead analysis (Sriprasert and Dawood, 2003).

As a concept LEWIS provided a substantial template for a production management system based on the Lean Construction concept that also integrated with product model. However, LEWIS still relied on the planner to carry out much of the planning and scheduling activities rather than enabling site users to manage the production planning and giving them access to product and process visualisation. Also, as the BIM applications were not developed at that time that offered parametric capabilities or had API (Application Programming Interface) to integrate to, LEWIS could not take advantage of the product visualisation fully. The implementation of the concept (system architecture) in the prototype also highlighted some limitations. For example, the Look-ahead planning module did not offer activity level planning, and excluded production level activities/tasks from Look-ahead planning. Instead it relied on the site team to add the sub-activities to Look-ahead plan once constraint analysis was carried out. However, constraint analysis relies on breaking phases and work-packages into smaller activities and analysing the constraints associated with them, which was not possible, hence a major limitation.

4.7.3 Bentley ConstructSim

ConstructSim is a virtual construction simulation software developed by Bentley for automated workplace planning in large projects. Amongst other features, it also provides partial ability to carry out Look-ahead planning, visualisation of production states (status tracking), and construction schedule animations. The Look-ahead planning is partly automated based on the status of the constraints, where the system dynamically tracks, updates and edits the work packages based on the status of the constraints. A screenshot showing constraints analysis feature is shown in Figure 18.

To visualise component statuses with construction status tracking, users mark and track individual model component or groups to see a colour-coded 3D image representing construction status. Construction work packages can be created visually, by organising components into construction work areas, construction work packages, and installation work packages.

The system also provides collaborative environment where the system can be shared with the suppliers and subcontractors.

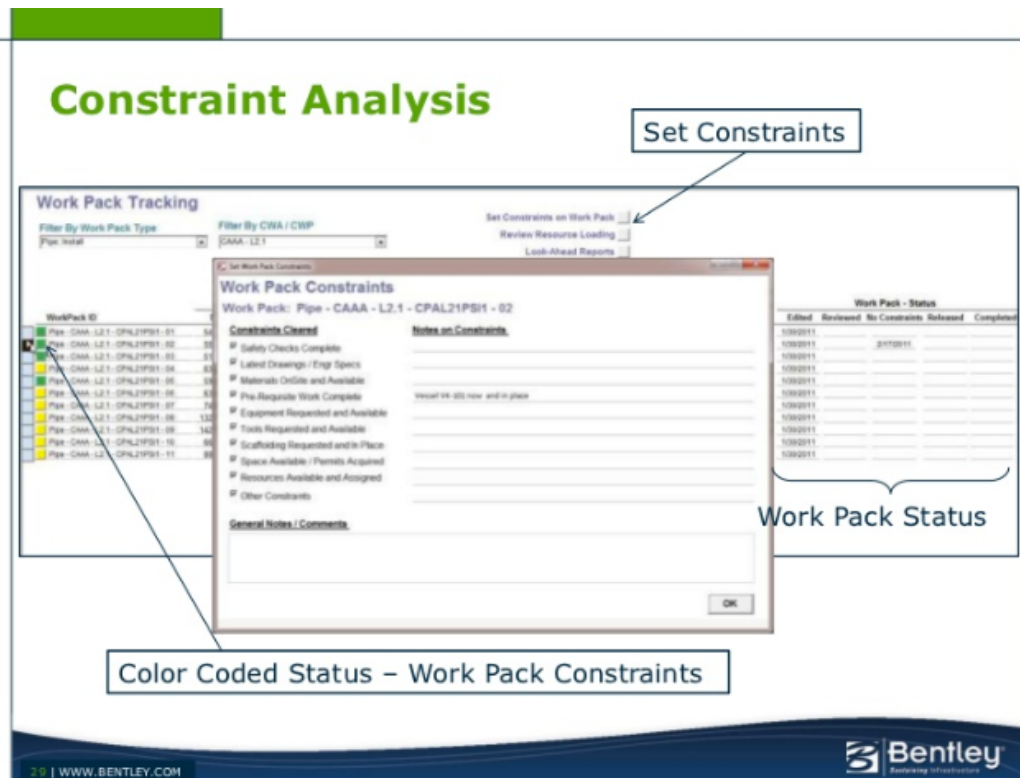


Figure 18. Constraints analysis with Bentley ConstructSim (Bentley, 2011).

Although, the system provides the ability to carry out constraints analysis, look-ahead planning and product and process visualisation, the software is aimed at planners and technical managers rather than the construction team or the Last Planners. Also, rather than providing information to the construction team and letting them take decisions about the planning and execution process, the system tries to automate this process, and also generates a list of pre-defined constraints. In ConstructSim, the focus on breakdown of activities and work packages is very similar to a CPM or a “T” based production planning and control method.

4.7.4 Integrated Project Scheduler

Chua et al. (2003) describe Integrated Project Scheduler as a person or a group who develops construction schedules with integrated information to improve the reliability of the production process, improve productivity and quality. The Integrated Project Scheduler is/are equivalent to the Last Planners as described in the Last Planner™ System. They propose a system based on the Lean Construction philosophy and the Last Planner process to enable computer based integrated

information management system for production. The key principles of the IPS system are defined as:

- Integrated information: Integrates supporting information (for example resource and information)
- Activeness: System actively responds to changes in construction and supports the pull flow in production
- Distributed system: Distributed system enabling collaboration between stakeholders and improving transparency.

Figure 19 demonstrates the principles of the IPS system in relation to the Lean Construction principles.

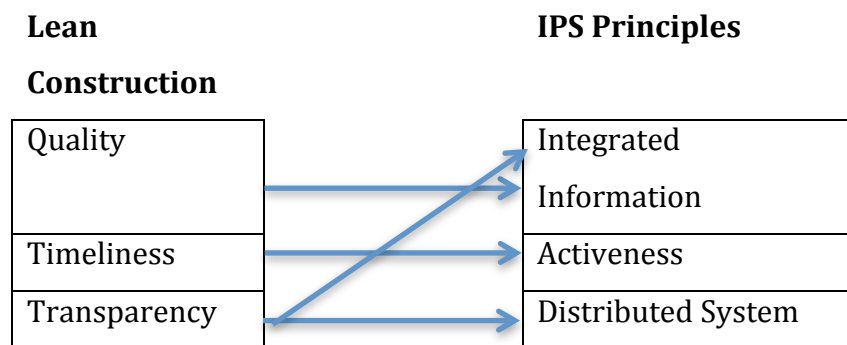


Figure 19. Principles of Lean Construction and IPS system (Chua et al., 2003).

The Integrated Project Scheduler was developed using JavaBean, XML database and Internet based communication. A prototype was created to demonstrate the functionality where a number of functions were demonstrated. Figure 20 shows the system architecture of the prototype system.

- Scheduling and supervising tool that helped produce and maintain a master IPS schedule and also look-ahead schedules. The system enabled data retrieval from the XML (Extensible Markup Language) database to keep track of constraints.
- The online messaging system allowed all stakeholders to interact with IPS schedule. The system enabled viewing the schedules, maintain relevant information through the XML database and JavaBean applets.

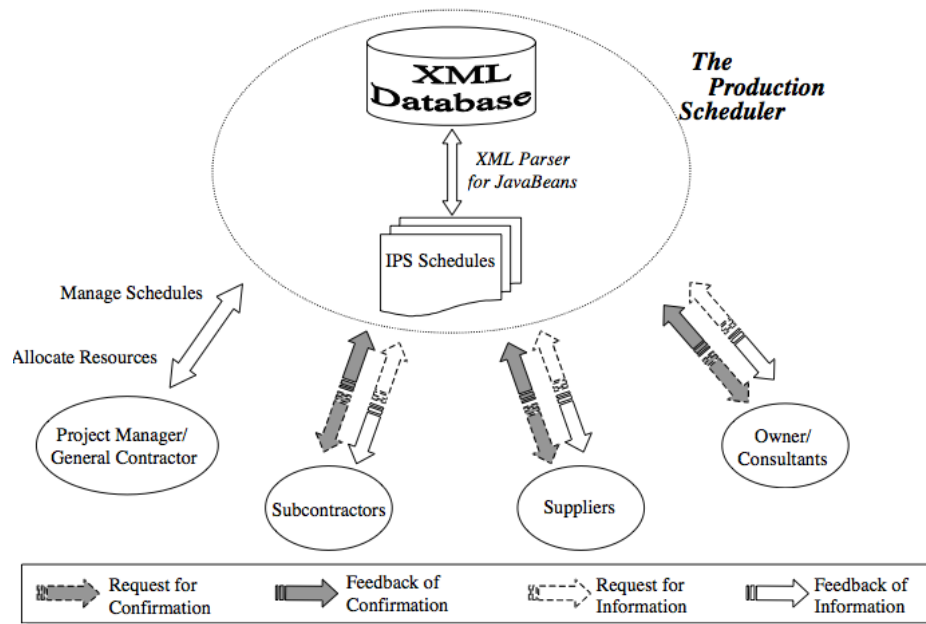


Figure 20. System architecture of the IPS system (Chua et al., 2003).

The IPS system only addressed the production management partially. It had the Look-ahead planning module, but was not developed as a complete production management system, which included phase planning and commitment planning. Also, it did not include product model (BIM) integration and did not involve the Last Planners in the process.

4.7.5 CONWIP (Sacks et al., 2009) and KanBIM

4.7.5.1 CONWIP: Sacks et al. (2009) developed a computerised system to enable pull flow scheduling based on visual processing signals that would be displayed on a board (a large computer screen). The main objective of the system to control “work in progress” by directing teams to work in locations where the work can be completed in a single uninterrupted sequence. This was achieved using visual symbols representing execution tasks that resemble traffic light system, and can be accessed by all crew members. Figure 21 demonstrates the status board generation interface.

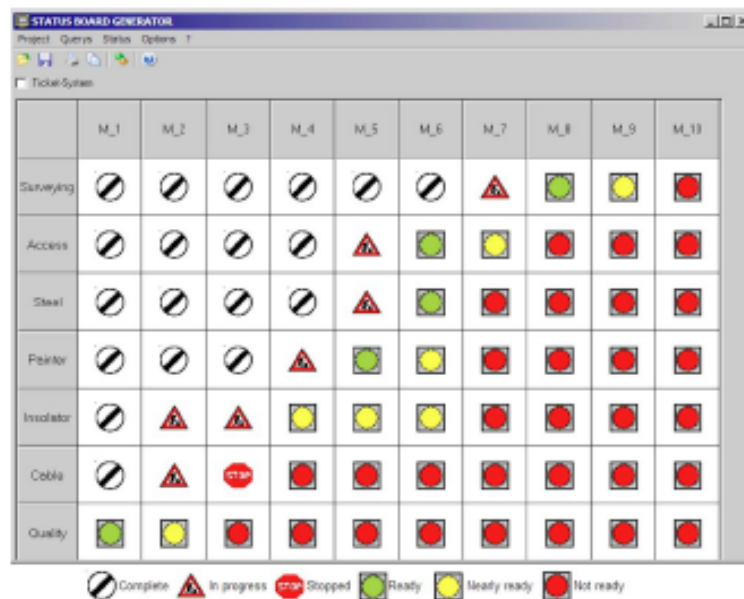


Figure 21. CONWIP Status Board Generator Interface (Sacks et al., 2009).

Sacks et al. (2009) also presented a system called WorkManager where the pull flow control interface was implemented to enable construction supervisors using tablet PCs “pull” the work according to their status, as opposed to the traditional “push” system of CPM. Figure 22 shows the pull flow signals used by the system to guide the supervisors.



Figure 22. Work Package status signals (Sacks et al., 2009).

To improve the visualisation and quality of information, the authors proposed a BIM based visualisation system that will also show the locations of tasks and their respective production status. Figure 23 demonstrates the visualisation capability system. The work statuses shown were tailored for each subcontractor to provide them visual information at a glance to help the plan and sequence the work in a more efficient way.

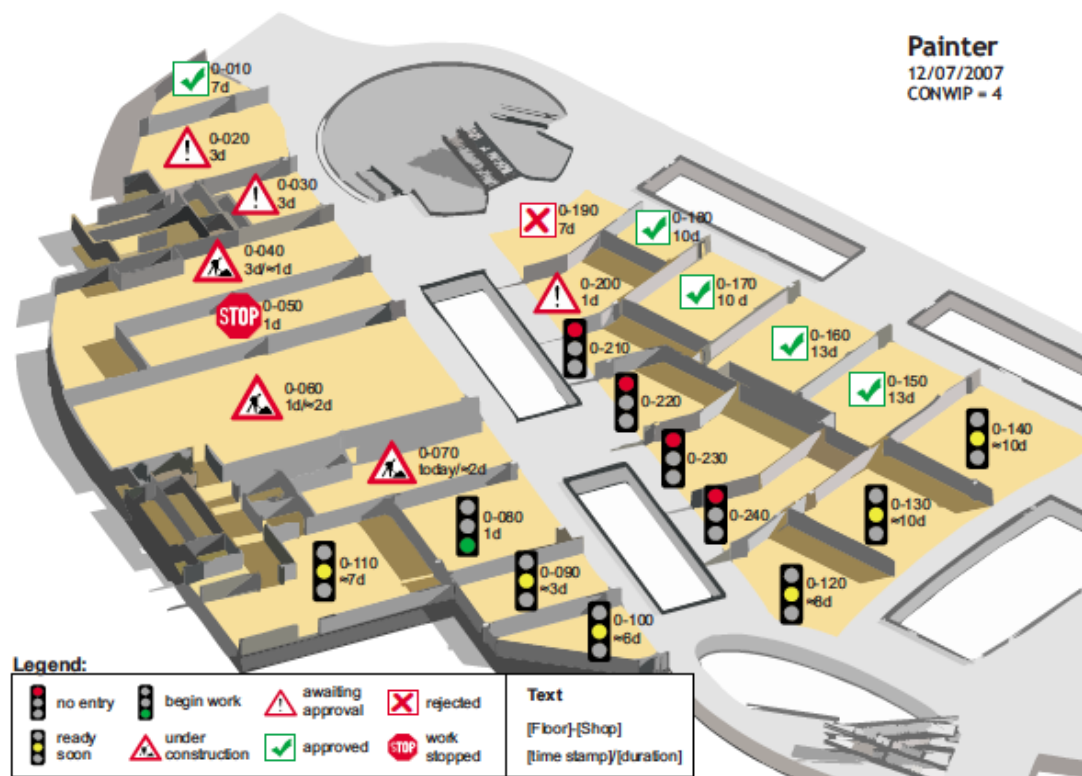


Figure 23. 3D visualisation of past, present and future work using CONWIP (Sacks et al., 2009).

4.7.5.2 KanBIM

Following from the CONWIP research, Sacks et al. (2010^b) have developed a research framework and prototype called KanBIM. The main goal of KanBIM research is to propose, develop and test a BIM-enabled system to support production planning and day-to-day production control on construction sites. They have specific a system based on initial analysis of literature in production control in construction and based on two case studies of construction management organisations in the UK.

The KanBIM planning and control process is based on the Last Planner System™ and allows phase planning, look-ahead planning and commitment/weekly planning. However, it extends the system by also enabling daily work assignments in the field. There were a set of application mock-up screens that were developed to demonstrate the functionality of the system. The concept has been developed by having the Building Information Model at the core of the system that provides

product visualisation over which a number of task status graphics are displayed. The system also implements an automated work maturity index that calculates based on the status of resource availability/constraint status the maturity of any given task. The idea of having the maturity index is to support the decision making process while selecting/considering tasks for execution. Figure 24 and Figure 25 show various functionalities of the KanBIM system through mock-ups.

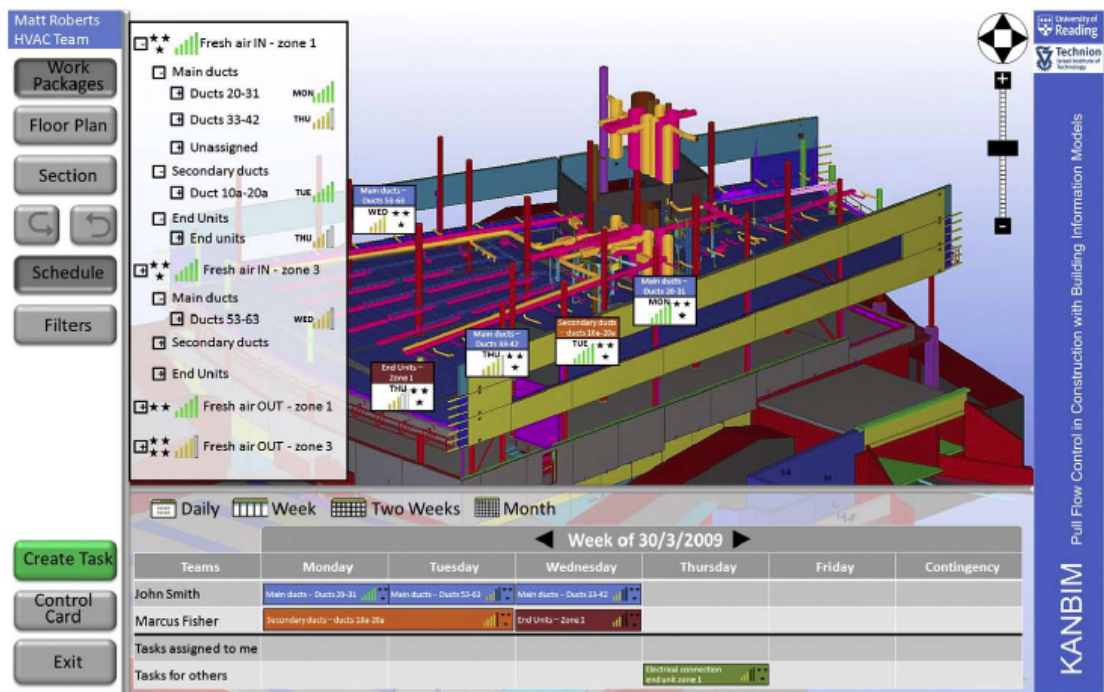


Figure 24. User interface for defining tasks and work packages (Sacks et al., 2010b).



Figure 25. Trade crew leader work status and reporting interface in KanBIM (Sacks et al., 2010b).

It would be important to note that there has been initial collaboration between the VisiLean research and KanBIM, however they are two separate systems with completely different system architecture and workflow. It was found early by both teams that their research idea coincide significantly and both emerged almost at the same time. Around the same time the both projects initiated the leading researchers from both teams collaborated to carry out seminar research by developing a conceptual framework between the interaction between Lean Construction and BIM which is discussed in the following section. Beginning in 2009, four collaborative workshops were organised in the course of the next 1.5 years, where significant exchange of ideas took place. It should be noted that these exchanges have influenced and informed the early research carried out in both KanBIM and VisiLean systems. However, due to the lack of any joint funding, the actual development of prototypes and further research including pilot implementations and demonstrations were organised individually.

Although there was no formal agreement or division of work, the VisiLean system dealt with the collaborative planning workflow and developing a production planning and scheduling system that would form the backbone (and the backend) of the overall production system, whereas the KanBIM system focussed on the field based activities, daily monitoring and progress of the production management and

control system. However, it should be noted that there is some overlap in the functionalities and overall concept between both the systems, and that they are complementary to each other.

Both, the CONWIP and KanBIM concepts represent an integrated production management system enabling visual product and process visualisation through Lean & BIM. The system covers all three aspect of the production system, transformation, flow and value and provides a comprehensive research framework. At the centre of both production management system is the concept of “pull” flow mechanism. It also supports collaboration between the construction team and are highly visual in nature. As mentioned above, both KanBIM and VisiLean research were contemporary and collaborative in nature, as a result VisiLean extends and complements both these research initiatives. This aspect is discussed further in Chapter 5 where VisiLean design and development are described.

4.8 Conceptual framework – BIM and Lean

Sacks et al. (2010a) have developed a conceptual analysis framework, which provides a mechanism to analyse the interaction between BIM and lean construction principles. The author was part of this research and co-author in the paper. This research laid the conceptual foundation for the VisiLean research, hence is important from that perspective. Here the authors have identified 56 unique interactions between BIM functions and lean principles. The authors list key lean principles (and sub principles) that were selected for analysis as outlined below in Table 12.

Table 12. Lean Principles (Sacks et al., 2010a).

Principal area	Principle
Flow process	<ul style="list-style-type: none"> Reduce variability <ul style="list-style-type: none"> Get quality right the first time (reduce product variability) Focus on improving upstream flow variability (reduce production variability) Reduce cycle times <ul style="list-style-type: none"> Reduce production cycle durations Reduce inventory Reduce batch sizes (strive for single piece flow) Increase flexibility <ul style="list-style-type: none"> Reduce changeover times Use multi-skilled teams Select an appropriate production control approach <ul style="list-style-type: none"> Use pull systems Level the production Standardize Institute continuous improvement Use visual management <ul style="list-style-type: none"> Visualize production methods Visualize production process Design the production system for flow and value <ul style="list-style-type: none"> Simplify Use parallel processing Use only reliable technology Ensure the capability of the production system
Value generation process	<ul style="list-style-type: none"> Ensure comprehensive requirements capture Focus on concept selection Ensure requirement flowdown Verify and validate
Problem-solving	<ul style="list-style-type: none"> Go and see for yourself Decide by consensus, consider all options
Developing partners	<ul style="list-style-type: none"> Cultivate an extended network of partners

Similarly, relevant key aspects of functionality that BIM technology provides for compiling, editing, evaluating and reporting information about building projects were selected. These are listed below in Table 13.

Table 13. BIM Functionalities (Sacks et al., 2010a).

Stage	Functional area and function
Design	Visualization of form Aesthetic and functional evaluation
	Rapid generation and evaluation of multiple design alternatives Rapid manipulation of a design model Predictive analysis of performance Automated cost estimation Evaluation of conformance to program/client value
	Maintenance of information and design model integrity Single information source Automated clash checking
	Automated generation of drawings and documents
Design and Fabrication Detailing	Collaboration in design and construction Multi-user editing of a single discipline model Multi-user viewing of merged or separate multi-discipline models
Pre-construction and Construction	Rapid generation and evaluation of construction plan alternatives Automated generation of construction tasks Discrete event simulation 4D visualization of construction schedules
	Online/electronic object-based communication Visualizations of process status Online communication of product and process information Computer-controlled fabrication Integration with project partner (supply chain) databases Provision of context for status data collection on site/off site

The Lean principles listed in Table 12 were then organised in a matrix as shown in Table 14. The bare matrix provides a framework for analysis of the interactions between Lean and BIM. The nature of interaction in any cell could be either positive or negative, representing synergy or inhibiting characteristics.

Subsequently, the matrix was populated with possible interactions between Lean and BIM and empirical evidence to support or refute the interaction was sought. 56 unique interactions as shown in Table 15 were found on the basis of emerging evidence from research and practice. Anecdotal evidence was found for most of interactions. It was identified that these interactions are not just limited to the design phase (where BIM technology is predominantly being applied currently) but extend to the production phase. All three interactions noted above either span

the entire lifecycle of the project or address specifically the production phase. For example, reducing product production (process) variability and reducing production cycle duration are all key from production management perspective.

Similarly, the BIM functions with highest concentration of unique interactions are:

- “Aesthetic” and functional evaluation
- Multiuser viewing of merged or separate multidiscipline models
- 4D visualisation of construction schedules and
- Online communication of product and process information

It can be observed that three out the four of the functions noted above are concerned with fabrication and construction management, indicating a strong synergy of Lean and BIM during the production phase.

Table 14. Lean & BIM Matrix (Sacks et al., 2010a).

Lean Principles BIM Functionality		Reduce Variability		Reduce cycle times		Reduce batch sizes	Increase flexibility		Select an appropriate production control approach		Standardise	Institute continuous improvement	Use visual management		Design the production system for flow and value				Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flowdown	Verify and Validate	Go and see for yourself	Decide by consensus consider all options	Cultivate an extended network of partners
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Visualization of form	1	1,2													3				4		11	5	6	4	
Rapid generation and evaluation of multiple design alternatives	2	1		22									7	7		8									
	3	9	9	22			51											1	16		5				
	4		10	12												8			16		5				
	5	1,2	1	12														1	1	1	5				
Maintenance of information and design model integrity	6	11	11																	11					
	7	12	12	22																	12				
Automated generation of drawings and documents	8	11		22	(52)	53											54	54							
Collaboration in design and construction	9			23						36						36									
	10	2,13		24				33											43		56	46		49	
Rapid generation and evaluation of multiple construction plan alternatives	11	14		25	(29)		31								(41)					44					
	12		15	25	(29)					37					(41)					44		47			
	13	2	40	25	(29)						17		40	40		40				44		47		49	
Online/electronic object-based communication	14		29	26	30	30			34					34			(42)					47	48		
	15	18		26	30	30			34		38		38	34			(42)				45			49	
	16	19		27			32																		
	17		20	28					35								(42)								50
	18		21		30	30			34			39					(42)					47	48		

Table 15. Lean & BIM Interactions – Explanation of cell content (Sacks et al., 2010a).

Index	Explanation
1.	Due to better appreciation of design at an early stage, and also due to the early functional evaluation of design against performance requirements (such as energy, acoustics, wind, thermal, etc) the quality of the end product is higher and more consistent with design intent. This reduces variability commonly introduced by late client-initiated changes during the construction stage.
2.	Building modeling imposes a rigour on designers in that flaws or incompletely detailed parts are easily observed or caught in clash checking or other automated checking. This improves design quality, preventing designers from 'making-do' (Koskela 2004) and reducing rework in the field as a result of incomplete design.
3.	Building systems are becoming increasingly complex. Even trained professionals have difficulty generating accurate mental models with drawings alone. BIM simplifies the task of understanding designs, which helps construction planners deal with complex products.
4.	As all aspects of design are captured in a 3D model the client can easily understand, the requirements can be captured and communicated in a thorough way already during the concept development stage. This can also empower more project stakeholders to participate in design decision making.
5.	Virtual prototyping and simulation due to the intelligence built in the model objects enables automated checking against design and building regulations, which in turn makes verification and validation of the design more efficient.
6.	With BIM, Gemba can be augmented because it is now possible to virtually visit the project and the worksite. With objects that contain intelligence and parametric information, problem solving is also more efficient.
7.	BIM provides the ability to evaluate the impact of design changes on construction in a visual manner that is not possible with traditional 2D drawings. Rapid manipulation is a key enabler for repetition of this kind of analysis for multiple design alternatives (see also item 40).
8.	It is now possible for multi-skilled teams to work concurrently in order to generate various design alternatives at an early stage using integration platforms such as Navisworks, Solibri, Tekla etc. as exemplified by the Castro Valley project case study (Khemlani, 2009). Also, at a later stage during manufacturing/construction; for any design change, changing the model will automatically update other relevant information such as cost estimating, project planning, production drawings, etc.
9.	Testing the design against performance criteria ensures that the design is appropriate for the chosen function, reducing the variability and improving the performance of the end product.
10.	Automated quantity take off which is linked to the BIM model is more accurate as there are less chances of human error; hence it improves flow by reducing variability. Also, changing the design at a later stage also changes the linked quantity files; this ensures that the quantities are always accurate.
11.	In sets of 2D drawings and specifications, the same objects are represented in multiple places. As design progresses and changes are made, operators must maintain consistency between the multiple representations/information views. BIM removes this problem entirely by using a single representation of information from which all reports are derived automatically.
12.	Use of software capable of model integration (such as Solibri/Navisworks/Tekla) to

Index	Explanation
	merge models, identify clashes, and resolve them through iterative refinement of the different discipline specific models results in almost error free installation on site.
13.	Multi-disciplinary review of design and of fabrication detailing, including clash-checking, enables early identification of design issues.
14.	Automated task generation for planning helps avoid human errors such as omission of tasks or work stages.
15.	Discrete event simulation can be used to test and improve production processes and to run virtual first-run studies, which in construction are often impossible or impractical.
16.	At the conceptual design stage, rapid turnaround to prepare cost estimates and other performance evaluations enables evaluation of multiple design options, including the use of multi-objective optimization procedures (such as genetic algorithms).
17.	Animations of production or installation sequences can be prepared. These guide workers in how to perform work in specific contexts, and are an excellent means for ensuring that standardized procedures are followed, particularly where turnover of workers from stage to stage is high, as is common in construction.
18.	When up-to-date product information is available online, the opportunities for identifying conflicts and errors within short cycle-times, when their impact is limited, are enhanced.
19.	Direct transfer of fabrication instructions to numerically-controlled machinery, such as automated steel or rebar fabrication, eliminates opportunities for human error in transcribing information.
20.	Direct delivery of information removes waiting time, thus improving flow.
21.	Provision of a model background and context for scanning bar codes or RFID tags, and display of the process data on model backgrounds, enables accurate reporting and rapid response to work flow problems
22.	Quick turn-around of structural, thermal, acoustic performance analyses; of cost estimation; and of evaluation of conformance to client program, all enable collaborative design, collapsing cycle times for building design and detailing.
23.	Parallel processing on multiple workstations in a coordinated fashion (with locking of elements edited on each machine) collapses cycle times of otherwise serial design activities. Where design was previously (i.e. with CAD) performed in parallel on different parts, the time needed for integration and coordination of the different model views is removed.
24.	Model-based coordination between disciplines (including clash-checking) is automated and so requires a fraction of the time needed for coordination using CAD overlays.
25.	All three functions serve to reduce cycle time during construction itself because they result in optimized operational schedules, with fewer conflicts
26.	Where process status is visualized through a BIM model, such as in the KanBIM system (Sacks et al. 2009), series of consecutive activities required to complete a building space can be performed one after the other with little delay between them. This shortens cycle time for any given space or assembly.
27.	Direct computer-controlled machinery fed directly from a model can help shorten cycle times by eliminating labour-intensive data entry and/or manual production, thus shortening cycle times. This does not guarantee shortened cycle times if the time gained is then wasted through batching or waiting.
28.	Removal of data processing steps for ordering or renewing material deliveries, removal of time wasted before ordering, etc., improve cycle times.
29.	In this case the functionality can be said to increase inventory of design alternatives. This can be considered beneficial in terms of making broader selections, delaying selection of

Index	Explanation
	a single alternative until the last responsible moment.
30.	Online visualization and management of process can help implement production strategies designed to reduce work-in-process inventories and production batch sizes (number of spaces in process by a specific trade at any given time), as in the KanBIM approach.
31.	Automated generation of tasks for a given model scenario and project status drastically reduces the setup time needed for any new computation or evaluation of a construction schedule alternative from any point forward.
32.	For numerically controlled machinery, data entry represents setup time. Direct electronic communication of process instructions from a model essentially eliminates this setup time, making single piece runs viable.
33.	Design coordination between multiple design models using an integrated model viewer in a collaborative work environment, such as those described in Liston et al. (2001) and Khanzode et al. (2006), enables design teams to bring multi-disciplinary knowledge and skills to bear in a parallel process.
34.	Process visualization and online communication of process status are key elements in allowing production teams to prioritize their subsequent work locations in terms of their potential contribution to ensuring a continuous subsequent flow of work that completes spaces, thus implementing a pull flow. This is central to the KanBIM approach, which extends the Last Planner System.
35.	Where BIM systems are integrated with supply chain partner databases, they provide a powerful mechanism for communicating signals to pull production and delivery of materials and product design information. This also helps make the supply chain transparent.
36.	Multiple users working on the same model simultaneously enables sharing of the workload evenly between operators.
37.	Discrete event simulation can reveal uneven work allocations and support assessment of work assignments to level production.
38.	Online access to production standards, product data and company protocols helps institutionalize standard work practices by making them readily available, and within context, to work teams at the work face. This relies, however, on provision of practical means for workers to access online information.
39.	Where BIM interfaces provide a context for real time status reporting, measuring performance becomes accurate and feasible. Measurement of performance within a system where work is standardized and documented is central to process improvement.
40.	BIM provides an ideal visualization environment for the project throughout the design and construction stage and enables simulation of production methods, temporary equipment and processes. Modeling and animation of construction sequences in '4D' tools provides a unique opportunity to visualize construction processes, for identifying resource conflicts in time and space and resolving constructability issues. This enables process optimization improving efficiency and safety and can help identify bottlenecks and improve flow.
41.	Detailed planning and generation of multiple fine-grained alternatives can be said to increase complexity rather than simplify management.
42.	None of these applications can be considered mature technology.
43.	Where clients or end-users are engaged in simultaneous reviews of different system design alternatives they can more easily identify conflicts between their requirements and the functionality the proposed systems will provide.
44.	Rapid generation of production plan alternatives can allow selection among them to be

Index	Explanation
	delayed (making the last responsible moment later than it would be otherwise). This can be considered to be a set-based approach to production system design and to production planning.
45.	Online access helps to bring the most up-to-date design information to the work face (although it cannot guarantee that the design information reflects the user requirements).
46.	Clash-checking and solving other integration issues verifies and validates product information
47.	Visualization of proposed schedules and visualization of on-going processes verifies and validates process information.
48.	Where managers can 'see' process status with near to real-time resolution, this may substitute for the need to see processes directly on site. However, it cannot substitute for seeing a process with one's own eyes.
49.	These functions can support and facilitate participatory decision making by providing more and better information to all involved and by expanding the range of options that can be considered. Of course, they cannot in and of themselves guarantee that senior management will adopt a consensus building approach.
50.	Integration of different companies' logistic and other information systems makes working relationships that extend beyond individual projects worthwhile and desirable.
51.	Use and re-use of design models to set up analysis models (such as energy, acoustics, wind, thermal, etc) reduces setup time and makes it possible to run more varied and more detailed analyses.
52.	Abuse of the ease with which drawings can be generated can lead to more versions of drawings and other information reports than are needed being prepared and printed, unnecessarily increasing drawing inventories.
53.	Automated generation of drawings, especially shop drawings for fabrication (of steel or precast, for example) enables review and production to be performed in smaller batches because the information can be provided on demand.
54.	Automated drawing generation greatly improves engineering capacity when compared with 2D drafting, and it is a more reliable technology because it produces properly coordinated drawings sets.
55.	Animations of production or installation sequences can be prepared. These guide workers in how to perform work in specific contexts, and are an excellent means for ensuring that standardized procedures are followed, particularly where turnover of workers from stage to stage is high, as is common in construction.
56.	Sharing models among all participants of a project team enhances communication at the design phase even without producing drawings, helping ensure that the requirements are understood and transmitted throughout the team and on to builders and suppliers

4.9 Summary of BIM

Building Information Modelling is a product management solution that has a potential to not only address the technological issues but also process and people issues. It covers the entire building lifecycle, from conceptual design to construction and hand over and facilities maintenance. There are specific functions within the production management aspect of construction, which are well served by BIM, such as simulation of a construction plan, or checking for

physical and process related clashes. Also, having a visual representation of a product model while constructing improves the understanding of the construction team from constructability perspective and reduces the chances for errors. Overall, BIM has a potential to reduce many inefficiencies attributed to the two dimensional design methods.

However, when combined, lean construction and BIM have even higher potential to address the shortcomings within the construction process as discussed in the sections above. This synergy of lean and BIM has the potential to address specific problems faced by the production management in construction and is considered further in the discussion below.

4.10 Discussion and Identifying Opportunities for a Solution

As discussed in Chapter 4, the problems associated with the construction process can be classified in two major categories: problems with the construction process and problems with the product representation (i.e. what is to be constructed). Also, as discussed in Chapter 3, currently available information systems for construction only address the peripheral processes and not the core construction process, which reduce their effectiveness (Koskela and Kazi, 2003). To improve the efficiency of the overall construction process, both the process and the product representation have to be efficient in their individual capacity as well as in an integrated capacity. Limitations of the traditional “T” based processes in construction such as CPM along with the limitations of 2D based product representation tools such as 2D Computer Aided Design were discussed.

As discussed, the lean production management system offers an effective way to solve the process related problems as it is based on the improved “TFV” theory. However, it only solves a partial problem, i.e. the problem related with process. Tools such as Visual Management, offer simple yet effective method of communicating production related requirements to workers. Building Information Modelling (BIM) systems through an improved product model, solve many of the problems associated with product visualisation. BIM also offers a solution to overcome many process related issues as it provides an intelligent

product model that resides in a visual platform. BIM can also be seen as a virtual Visual Management platform for the production management process.

The efficiency of the production planning and control process in construction depends significantly on the reliability and timely availability of resource information. However, this information is not readily available due to the lack of systems integration that prevails within the industry.

As observed, current implementations of the LPS™ mostly rely on the team leaders' and foreman's ability to gather required information for the weekly planning meetings and also for the look-ahead planning. However, much time is wasted chasing relevant information due to the lack of a production management system. There is a gap in the market/field as the lean construction processes are not effectively supported by the Information Systems, even though much of the project information now exists electronically. The current 3D and 4D BIM systems that provide a master plan level overview of the project, the true capabilities of Building Information Modelling systems are not exploited enough during the production management stages.

The conceptual Lean and BIM framework clearly demonstrated the potential for these two initiatives during the production management stages, which have also been proven through previous case studies. The existing research in Lean and BIM production management systems also demonstrate the potential, however, with the exception of KanBIM none extend to field or provide support for the Lean Construction workflow.

Subsequently, from the literature review and industry feedback, it emerges that there is a distinct potential for a system that can integrate lean construction to Building Information Modelling systems. The interest of construction organisations in BIM is increasing. This view is supported by the BIM SMartMarket report (2009), where findings suggest that the percentage of contractors who use BIM is expected to rise from 11% to 54% by 2012, as they perceive BIM as a valuable tool. At the same time the use of BIM on construction sites is also increasing. However, the construction organisations are constrained by the limitation of available BIM solutions that support on-site construction

activities. This view was also reflected in the BIM SmartMarket report (2009), where 54% contractors said that they use BIM on 11% of projects and expect that number to increase to only 30% by 2012. Overall, it emerges that there is a need for a software system that would support site based construction activities, especially by integrating lean and BIM.

5 Designing and Developing VisiLean: A Production Management System

From the discussion in Chapters 3 and 4, it emerges that there is a clear need for a software system that supports the full production management lifecycle. Such a system would support the lean production management workflow on the job site itself and would be designed to support the production crew/site teams (i.e. the Last Planners). The system will primarily address two major strands of the production system:

- Production management process representation
- Product representation and visualisation

Additionally there are further requirements to support the

- Integration of resource information (such as procurement, inventory, personnel, etc.),
- Communication between operatives and
- Delivery of accurate reports to facilitate better decision-making.

A conceptual research framework and a prototype based on that framework have been designed and developed during this research. This Chapter describes the design and development of the framework and the prototype.

This Chapter is divided in two main parts, namely:

- i. Designing the framework – this section describes the key requirements gathered from the field (through interviews, workshops and meetings) and from previous research.
- ii. Developing the prototype – this section describes the development methodology, functional requirements, system architecture and the steps taken to develop the VisiLean software system.

5.1 Designing the framework

The framework and the prototype developed are designed to support the lean production planning and control method that is based on the Last Planner™

method of production planning and control. An explanation of the Last Planner™ workflow has been provided in section 4.2.1.

While designing the framework, the following process was followed:

- i. Gathering feedback from practitioners regarding current practice in use of Lean and BIM in production management
- ii. Gathering general production management requirements from literature
- iii. Gathering and analysing requirements from previous research initiatives in advanced visualisation techniques in production management
- iv. Defining a set of requirements for a production management system

Before initiating the design of the solution to any problem, it is necessary to understand the problem in its proper context and then define the key requirements. In previous Chapters, the main problems being faced during the production management stage of construction were discussed. However, for the sake of clarity the key problems of the production management system in construction are summarised as below:

- i. Absence of production management system that support the “Pull” workflow
- ii. No support for detailed constraints analysis and collaborative analysis of the plan
- iii. Lack of integration of other information sources such as procurement and design management
- iv. Lack of audit trail of decision making during scheduling
- v. Lack of integration with the product model (BIM)
- vi. Problems regarding spatial awareness during planning/execution (due to the use of 2D drawings)

To gain deeper understanding into the problems faced by the construction personnel during the production planning and control stage, feedback was gathered through workshops, focus group interviews. Further feedback was also received during the demonstration of the prototype, which improved the understanding of the problem.

5.1.1 Gathering Feedback from Practitioners

In addition to feedback received during workshops and demonstrations, feedback was also gathered during a pilot project, which was carried out on a Highway Automation project (where traffic management infrastructure were being installed) in the UK.

Although the workshops and meetings did not follow a structured questionnaire approach and were mostly open-ended discussions, where possible following questions were asked while gathering feedback.

- What challenges are being faced (technical and process related) while implementing the production management system
- What BIM solutions are being used to support the production management system
- Are you using Lean Production Management techniques on your project(s)?
 - If so, do you think they are adequately supported through existing Information Systems?
- Do you use BIM on your projects?
 - If so, are you using BIM for production management and to support lean processes?

The following paragraphs outline the main feedback received during the initial feedback sessions.

5.1.1.1 Production management systems mostly rely on manual information retrieval

Even after almost two decades following the launch of International Group for Lean Construction and numerous construction organisations around the world having adopted lean practices, hardly any software systems exist that specifically support the lean production process. Collaborative planning sessions, namely reverse phase scheduling, look-ahead planning and weekly/commitment planning rely mostly on manual processes where stakeholders use Post It™ notes or similar devices to plan and sequence construction activities. Following from

the planning sessions, the information is mostly managed using paper based plans or at most Excel spread sheets or similar systems.

Observed by the author, on two UK based projects where collaborative planning was implemented, besides following the Post It™ method, five separate spread sheets were being maintained, along with three paper based registers to collect and manage information from the planning meetings. This was in addition of the project planning and scheduling system Primavera Project Planner, and Enterprise Information Management system. None of these systems were integrated with each other causing a significant amount of data re-entry. Use of such a system is inefficient as it cannot easily integrate information from other management systems and is not standardised across projects.

Another key issue that was highlighted by the practitioners was that little auditing is possible with the current systems, i.e. when key decisions are made regarding (re) scheduling tasks, reallocating resources, etc., it is currently not possible to record such decisions. Hence, it is not possible to track the performance of the project and link back to these decisions and learn from it (i.e. whether it impacted positively or negatively). Similarly, reports such as the PPC (Percentage Plan Complete) and Reasons for Non Completion are created manually either by the site manager or by the site planner. The data is collected manually and such reports are prepared in Excel. Such tasks are very time consuming and as a result costly.

5.1.1.2 Use of BIM is still limited to Clash Detection and 4D

It was observed through all interviews and workshops that the participants felt that the availability of BIM model provides them a significant opportunity to use it throughout the construction project. Although use of BIM is increasing on the construction site, it is still limited to basic 4D simulation where a master plan is attached to the model and the project schedule can be simulated in 3D at a macro level. There are some systems, which enable detailed resource management and 5D planning, however these systems are highly complicated and rely on dedicated system operatives who have been trained to use these systems. Due to this high level of training and skill required and relatively high cost of

implementation, it is not possible to yet implement these systems across the whole supply chain so that they can be used throughout the construction process. As a result, these are mostly used during the initial stages of the project to develop detailed schedules, but not during the production management operations.

It emerged from the interviews that two organisations were already using BIM during their collaborative planning sessions. However, this was achieved by having a dedicated BIM manager who helped with the navigation of the BIM model while the tasks are being discussed during the collaborative planning session. When these BIM managers were interviewed, it was mentioned that due to the lack of direct connection between the planning tasks and BIM system, the navigation becomes a difficult activity and sometimes results in longer than usual time taken to carry out these meetings.

5.1.1.3 Field BIM is now increasingly becoming accessible due to advanced hardware and maturing/new software

Use of BIM technology on construction sites is increasing due to the advantages that it provides such as physical and process clash detection as well as clarity on the design intent. Some case studies such as Castro Valley project (Khemlani, 2009) and Maryland General Hospital (Eastman et al., 2011) are such examples where BIM has been utilised quite successfully along with other tools and techniques such as lean construction. In two case studies the author observed, one in Chicago, US and other in Bristol, UK, it was found that a workstation (high end computer) was made available to construction teams to access BIM models during execution. This enabled the workers to gain a better understanding of what is to be constructed (i.e. task at hand) and reduced the need for supervisory communication. However, as the BIM models are only the partial representation of the project (i.e. only the product model), the process side was not available in the same interface.

It was also found that construction companies were looking for innovative solutions to take BIM to the worksite using mobile technologies, however were restricted by the options available to them. There are currently only a couple of

software platforms such as Vela systems (now acquired by Autodesk) and Artra (in the UK) that offer field management of construction using mobile devices and also partial integration with BIM model.

5.1.1.4 Summary of feedback

Although the popularity of BIM is increasing on construction projects, from the user workshops and interviews, it was found that not many software systems exist that go beyond macro level 4D planning. Hence, construction personnel are left to devise their individual solutions on their own. In case of some organisations, they hire a trained BIM technician or architect to personally facilitate use of BIM during daily construction activities and other planning sessions, however, this is yet to become an industry wide practice, and one that is not yet supported by commercially (or otherwise) available systems.

5.1.2 Gathering general production management requirements

In the following section, the key requirements for a production management system are outlined, which are classified under two main categories, functional and technical.

As such, the lean production management workflow as a whole has to be supported by the proposed framework and system, which forms the major part of the functional requirements. Additionally, there are requirements to support the sharing of information internally within the processes and externally to members of the construction/production team (that form part of the implicit and explicit communication). Also, there are requirements for the user interface that partially overlap with functional and technical requirements. Figure 26 describes the three types of requirements that form the overall system requirements.

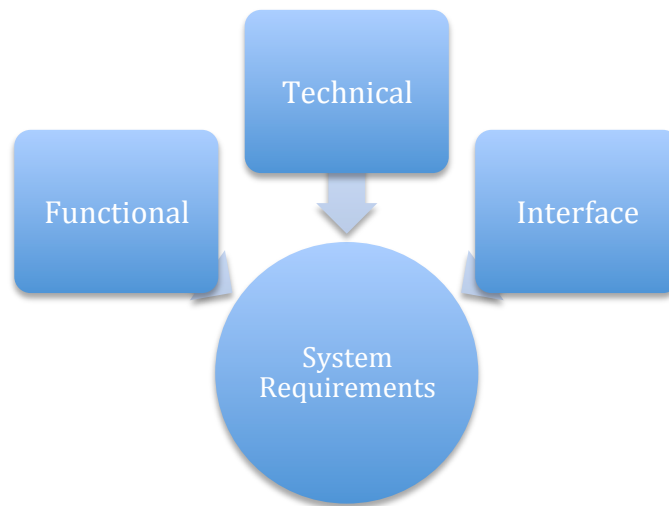


Figure 26. Types of Information System Requirements.

Ballard (2000) in his seminal work on the Last Planner System™ describe the following requirement from a production control system, which are considered from the production management perspective:

- Variability must be mitigated and remaining variability managed
- The traditional schedule-push system is supplemented with pull techniques
- Production control facilitates work flow and value generation
- The project is conceived as a temporary production system
- Decision making is distributed in production control systems
- Production control resists the tendency toward local sub-optimisation

Additionally, the following five principles outlined by Koskela (1999) for a production control system are relevant and considered:

- Assignments should be sound regarding their pre-requisites (i.e. free of constraints)
- The realisation of assignments is measured and monitored (such as the Percentage Plan Complete measure in the Last Planner System™)
- Causes for non-realisation are investigated and those causes are removed
- A buffer of unassigned tasks which are sound for each crew is maintained
- In look-ahead planning, the prerequisites of upcoming assignments are actively made ready

The above requirements are fundamental to this research and are taken as implicit requirements, which are then translated in explicit functional requirements and subsequently system architecture.

5.1.3 Capturing Requirements from Previous Research into Advance Visualisation in Production Management

As discussed in Chapter 4, there have been a number of attempts regarding a production management system that addresses the lean production control along with integration with product model (such as BIM, CAVT, VDC, etc.). The following section discusses the requirements presented by such initiatives on a production management and control system.

5.1.3.1 Factors to improve construction management on site

In an earlier study on the simulation of information flow to help design decision-making, Hassan (1996) identified the following factors to improve the management of construction site management processes and coordination of activities.

- Schedule creation through 4D models, which help visualise schedule constraints and opportunities for improvements through re-scheduling and reallocation of workspace.
- Schedule analysis: 4D models help analyse schedules and visualise conflicts that are not apparent in Gantt charts and CPM programmes.
- Communication: To help improve the stakeholders' understanding of project activities and the product (structure) to be built
- Team building: To support and improve collaboration through a shared, visual model that is capable of communicating and sharing project issues.

5.1.3.2 Lean Enterprise Web-based Information System for Construction – LEWIS

Sriprasert and Dawood (2003) put forward the following requirements for a production management system:

- **Consideration of the level of planning and collaboration:** Here it is meant that the production management should be able to support the planning and scheduling not only at the master level, but also at the look-

ahead planning and weekly level, i.e. fine grained planning should be supported.

- **Consideration of constraints:** The flow aspect of the production management, i.e. management constraints that are defined previously in Section 3 should be supported by the system. These constraints (including physical, design, and contract related) must be effectively communicated, evaluated and removed before releasing the assignments (tasks) to workers.
- **Handling uncertainty:** Uncertainty in production must be recognised and proactively absorbed by inserting appropriate buffers into project schedule.
- **Visual representation:** Advanced visualisation techniques should be used to evaluate and inform planning output. The advanced visualisation can also be supported by simple tools such as worksheets and bar charts while issuing instructions to the work crew.

5.1.3.3 4D requirements for Planner's Information Visualisation System

Aranda-Mena et al. (2004) present requirements for 4D development for a planner's information visualisation system. The authors identify the following key factors:

- Reduce sources and effects of uncertainty
- Create conceptual "what-if" scenarios (reducing variability)
- Provide friendly user interface and tools
- Assist in decision-making on time and resources

5.1.3.4 Lean Production Management System Requirement

Sacks et al. (2009) present a set of lean construction management requirements as shown in Table 16, for both planning and control, and examples where Computer Aided Visualisation Tools (CAVT) can support them.

Table 16. Lean Construction Requirements and CAVT Support (Sacks et al., 2009).

Lean construction requirement	Computer-aided visualisation tools
Production System Design and Production Planning	
Plan for stable work – plan project activities effectively, predicting problems and safety issues	4D CAD modelling including space resources and temporary facilities (Akinci et al. 2002; McKinney and Fischer 1998)
Communicate standardised processes to workers	Modelling of production details using BIM and 4D CAD animation videos
Production management and control	
Monitor production and record performance benchmarks for improvement experiments	Visual tools for input of production data
Make process transparent to all	Electronic status boards can show current status of tasks. Progress can also be displayed by superimposing 4D colour coded images on site photographs (Fard and Pena-Mora 2007)
Filter work packages for maturity to ensure stability	The Last Planner System™ (Ballard 2000) can be supported by visual status charts that show the readiness of equipment, materials, space, information, etc. BIM can support dynamic safety conscious work filtering using the CHASTE model (Sacks et al. 2007)
Pull technical information for work packages when needed	On-line pull of up to date drawings and other information from a BIM server (Sacks and Derin 2006)
Provide pull flow signals to regulate work flow	Work in progress is not visible, like in manufacturing, so directives to action pull work. On-line pull flow is needed and must be communicated to teams (Sacks and Goldin 2007)
Pull detailing and fabrication/assembly of building system components according to short term planning to match production flow	Collaborative detailing with integration across disciplines (Khanzode et al. 2005)
Just-in-time delivery of material and parts	BIM can provide accurate and automated preparation of bills of materials for JIT delivery (Chau et al. 2004) Color-coded interface for giving pull signals
Pull management attention to where it is needed, to release bottlenecks or facilitate flow	Visual production flow monitors and safety risk levels can be used to attract management attention to nodes of instability or danger, e.g. use of Andon lights (Pereira 1998) and the CHASTE model (Sacks et al. 2007)
Respond flexibly to change	Design or process changes can be disruptive. Visual planning interface can enable managers to adapt construction plans/material and resource orders/work assignments flexibly and responsibly

5.1.3.5 BIM based Lean Production Management Requirement

Following from the CAVT research, in a recent research which integrates Lean Construction processes with Building Information Modelling, Sacks et al. (2009) outline the requirements for a BIM based lean production management system for construction, which are discussed below.

Process visualisation: It is suggested that the status and location of work teams and the real-time maturity of pending tasks are displayed to support the negotiation and reporting of plan changes on a daily level. It is also suggested the system must enable communication and feedback of decisions. Such production status related information should be overlaid and integrated with a BIM platform where it would be possible to filter/query the objects for their relationships with work packages and relevant status.

Product and method visualisation: Here the authors highlight the need to take the product and method visualisation to the “coal face”, i.e. to improve the availability of such information to construction workers in the field. The authors suggest a large touch screen device (such as a Plasma display with touch overlay) that enable individual or group/collaborative viewing of product and method visualisation.

Computation and display of work package and task maturity: Task maturity is defined as a measure of the state of readiness of a work package or a task, and is an evaluation of the degree to which any constraints pre-conditions have been released. Two main functions of the maturity index are put forward, to support short-term decision making by team leaders before committing to a task and to support weekly planning activities. The maturity index is calculated automatically by the system as a composite of the maturity measures of each distinct pre-conditions (i.e. constraints and is time dependent (i.e. is different at any given time)).

Support for planning, negotiation, commitment and status feedback: This requirement corresponds to the recognition that the conceptualisations used to at the planning level are not in sufficient level of resolution to be applied to the production level. As a construction project is a highly dynamic environment,

production planning has to respond to the changing situation on almost a daily basis, where relationships between trade teams (negotiations about work sequence, space utilisation, etc.) has to be managed effectively, in order to prepare conflict-free and coordinated work plans. The production management system should support that, hence agility is needed. Following requirements are put forward by the authors in support of this:

- Tightly integrate planning and production control. The granularity of the weekly work planning and the level of detail of task properties must be appropriate for daily production control
- Enable online feedback from the workforce to ensure that the process status information is up-to-date
- Provide a channel of communication for negotiation of changes to planned tasks, reducing the planning window to daily level, extending the Last Planner System™. This requires enabling the trade team leaders to propose plan changes, identify and resolve any resulting conflicts through negotiation with the affected parties, and inform all other project participants of resulting changes
- To improve the reliability of planning and coordination on construction projects, use of language/action perspective is recommended. Language/action perspective refers to the idea that creativity in projects is coordinated through making and keeping commitments rather than by directives from managers. Language/action perspective recommends a system or a process of request, commitment, action and reporting completion. It is suggested that the production management system should incorporate/support the language/action perspective by facilitating the reporting of start and completion or stoppage of tasks.
- It is proposed that the production management should recognise the fact that the work planning and coordination is a human/people centric activity and the software is supporting the collaboration and coordination rather than replacing it. The system should also recognise the chain of authority and that the final authority in resolving any conflict should lie with the project construction manager.

Implement pull flow control: It is proposed that an online (visual) process status displays should be used as a means to communicate pull signals to work teams to facilitate “pulling” of work. The key principle (similar to the KanBan system) is to reduce the work in progress (and in turn inventory), which is considered to be one of the most abundant wastes in production systems. This strategy can be applied individually to one trade contractor or collectively to multiple trade contractors if there are connected or concurrent tasks, where teams are competing for space or other resources. A probability index called “pull flow index” which is defined as a “measure of the likelihood that the sequence of tasks following the current task, that is needed to complete a zone or product, can be performed continuously to completion.” is proposed to be used by construction managers while setting task priorities. It is also advised by the authors that contingency tasks, which are completely free of constraints and not connected to contemporaneous tasks, should be used to add short-term flexibility and to act as a buffer.

Maintain work flow and plan stability: It is stated as a requirement that to ensure stable work and to minimise the occurrence of “making do”, any tasks which are executed must be recorded in the system and that no “ad hoc” changes should be allowed during the week once the plan has been agreed by all stakeholders. Also, any failure due to unavailability of a part or an error in its fabrication or design information should be made transparent and not hidden by removing that task from the plan.

Formalise experimentation for continuous improvement: It is suggested that the system should allow for structured experimentation by selecting one or more specific tasks each week and flagging them up (visually) as experiment tasks, along with a definition of what the goal of the experiment is and how it will be measured. It is suggested that such formalised experimentation would lead to continuous improvement on current and future projects.

Sacks et al. (2009) have also described different aspects of construction planning and control operational at various levels on the project as shown in Table 17. It is

important to understand this while designing a new system as planning processes at all levels must be catered for.

Table 17. Aspects of construction planning and control at various levels (Sacks, 2009b).

Planning level	Master planning	Look ahead planning	Weekly production control
Aspect			
Resolution Goals	Milestones	Work Packages	Tasks
Methods for definition of planning unit	Top-down division of project duration	Top-down division of milestones into activities	Bottom-up aggregation of parts into a task
Tools and Measures	Contract terms, critical path method and process optimisation	Critical path method; constraint release; maturity index; and line of balance scheduling	Pull priority; negotiated team coordination; and maturity index
Relationships	Contractual	Hard technological constraints (such as FS); resource leveling and space conflict resolution	Flexible working relationships/resource and space coordination
Primary Planning Responsibility	Construction Manager	Construction manager in consultation with trade managers	Trade team leaders and managers

5.1.4 Discussion about the requirements from literature

There are two types of requirements that were covered, one that are principal requirements from a production management system as put forward by Koskela (1999) and Ballard (2000), which were considered as the core guideline when developing the solution. Secondly, requirements that are extracted from previous research initiatives in developing production management and control system, where integration of product and process modelling has been considered as discussed above.

The following six factors are extracted from Koskela (1999) and Ballard (2000) to form the basic requirements of a production management system:

- Supporting flow (workflow)
- Reducing variability through sound assignments
- Supporting pull techniques

- Measure and monitoring to support continuous process improvement
- Maintaining a buffer of unassigned tasks
- Supporting distributed decision making through collaboration

Sacks et al. (2009, 2010b) have provided comprehensive requirements for a computerised production management system that integrates process and product visualisation. Sriprasert and Dawood (2003) have also highlighted key requirements for a visual production management system that takes into consideration the Last Planner™ approach. Overall, the above-mentioned requirements from previous research cover most aspects of production management including the integration of product and process modelling. Although there are subtle differences in the context and detail at which each research has addressed these requirements, and also there are differences due to the chronological gap between the research period (and technology changing rapidly in during this period), there are significant overlaps between them. These requirements are taken on board at a high level of abstraction, however there are additions made, where the detailed requirements are outlined later in 5.3. The main difference between VisiLean and the above mentioned research is that VisiLean is designed to be used directly by the production crew on site and is meant to be a simple yet effective solution that integrates process and product representation in a visual way. Some of the major differences are outlined in the discussion following Table 18.

5.1.5 A Critical Review of Previous Research

Previous efforts in improving production planning and control were reviewed in Section 5.1.3. While they provide valuable information that can be considered while designing a production management system, they are not complete and do not address some critical aspects that emerged during the problem identification and literature review. While Hassan (1996) provides a high level framework to improve construction management through use of 4D visualisation and simulation of information flow, there is no detailed framework provided to tackle aspects such as the specific information flows, constraints analysis or the production planning workflow such as the Last Planner™ system. Some commercial systems such as Autodesk Navisworks, Tekla Structures

(Construction Management), Vico Control etc. are understood to be providing such features now, however, they only partially address the problem as has been discussed previously. Sriprasert and Dawood (2003) provide a framework in LEWIS for a production-scheduling platform using constraints analysis and visual representation. Although there is a consideration of constraints analysis and visual representation of the process, the system is predominantly designed for head-office based planning and scheduling activities, which will push the plans to the site, as there are no specific interfaces designed for site based collaborative planning or control activities. Aranda-Mena et al. (2004) have provided a high level framework for 4D development of a planner's information system. Although the requirements are relevant, they are not detailed and do not specifically address site based production planning or scheduling. Also, there is no mention of simultaneous visualisation, integration and synchronisation of process and product views or constraints analysis and production control activities. Sacks et al. (2009) provide a summary of requirements for a production management system. Although the requirements are comprehensive, they do not constitute a single integrated system meant to address site based processes, but distributed systems that partially address the requirements. Sacks et al. (2010) subsequently have proposed a set of requirements in design of their KanBIM system, which are discussed separately in section 5.1.6. To summarise, none of the previous requirement compilations comprehensively provides a framework for a system that addresses all three aspects in a production management system that emerged as critical requirements in Chapter 3, i.e. those of simultaneous visualisation, integration and synchronisation of product and process. Also, not all the requirements are directly addressing a production management and control system designed for site-based activities and supporting a lean workflow. However, some of these requirements are still relevant to the design of a production management system and are taken into account while designing VisiLean.

5.1.6 Defining VisiLean Requirements Framework

Following key aspects emerge from the study of literature, which are shown in Table 18. These aspects along with feedback capture from practitioners are taken into consideration while designing VisiLean.

Table 18. Defining VisiLean requirements.

Requirement	Discussion
Process and product visualisation at the “coal face”	This is one of the most significant and overlapping requirement that emerges from past research (and also from prior case studies and exploration of the problem area). This means that the information regarding the planning and scheduling, along with the relevant design information (that forms the product model) should be made available to workers (construction team) on site.
Supporting constraints analysis and management	This is also an essential requirement for a production management system and an aspect that is often neglected in most current systems. The system should allow the teams to identify, analyse and assign constraints. Once assigned the system should also allow tracking the status of the constraints linked to the tasks. Finally, analysis in the efficiency of removal of constraints should also be facilitated.
Supporting collaboration, work negotiation and communication between the project team	Addressing people issues, building trust, improving coordination and communication and securing commitment to the production plan are some of the most critical issues that a new system has to address. All previous research initiatives recognise this aspect and put forward collaboration as a key requirement for a production planning system. Collaboration spans the entire lifecycle of the project, starting from lean work structuring and continuing to look-ahead planning, weekly commitment planning and daily execution, feedback and coordination (including start-stop signals). The other key aspect to be recognised is that the production management process is a highly people centric and the goal of the computerised system should be to support the collaboration rather than automate the process. Many previous attempts have failed where the users have been alienated from the system due to high level of automation or the complicated nature of the system.
Enable “pull” flow control and plan stability	From lean perspective, “pull” production management is a key to reduce variability, which is one of the biggest enemies causing waste and uncertainty on construction. All previous researchers have identified the need for the system to support a combination of “push” and “pull” techniques to maintain plan stability and reduce variability. As can be observed in Table 13, the system should support the workflow starting from Master Planning and Phase Planning going on to Look-ahead plan and then weekly planning and daily execution. During this process the key aspect is that the system enables the users to create a workable backlog of constraint free tasks, which can be selected based on their priorities to improve flow and reduce work in progress, while also supporting coordination by signalling to downstream crew when the preceding task is completed.

Koskela (2000) presents the TFV (Transformation, Flow and Value) framework to tackle production in construction. He claims that all these three conceptualizations of production are necessary and that they should be utilized simultaneously. This is one of the most fundamental, theoretical frameworks from lean perspective that the VisiLean system should address. Table 19 describes the specific features within VisiLean that address the TFV requirements.

Table 19. Addressing TFV through VisiLean.

VisiLean Features	Transformation	Flow	Value
Planning and Scheduling	Task Planning, and Scheduling- in Phase, Lookahead and Weekly Planning (software) interfaces help to maintain consistency in task specification.	Managing the flow of resources through constraints analysis and management. Assigning constraints to tasks and also the responsibility to manage them to workers and teams.	Reduction in making-do through improved performance of constraints removal process, leading to better performing planning and scheduling system leading to sounder tasks, less rework and better quality.
Task Management	Assigning task completion responsibility at the Last Planner level to workers.	To make input flows visible through linking of constraints to tasks (and their current status).	
Simultaneous Visualisation of process and product	Visualisation of task information in process and model views, i.e. where and when the task is supposed to be executed.	Managing the flow of work between long term, medium term and short term planning processes.	Reduction of confusion through joint appraisal of production plan in both process and product views, improving the quality of work and reducing risk of rework and delays due to misunderstandings.
Production Control	Production control features of starting, stopping and completing tasks and their visualisation in both the model and process views.	Managing and visualising in process flow between production tasks by Visualisation of task statuses in both product and process views.	Visibility of upstream task completion to downstream stakeholders.

One of the requirements put forward by Sacks et al. (2009) is that of maturity and pull flow index. Although providing construction teams an indication of the

task maturity based on the status of the constraint seems beneficial, the associated risk regarding the accuracy is too great for it to be considered viable. As a construction project is a highly dynamic requirement and availability of resources change constantly the construction managers and trades foreman are the best judge when it comes to making decisions regarding resource availability, and the final decision is best left for a human to make rather than a computer. The same applies for the “pull flow” index as it depends on the maturity index along with the status of connected tasks. As a result, these two features were not implemented in VisiLean.

Also, majority of the systems discussed above did not put forward a requirement for information sources to be aggregated in the production system so that the information availability at the decision making point is improved. For example information about various resources could reside in information systems belonging to main contractor, subcontractor or other stakeholders. Traditional methods for integration of these information sources have been through direct links established between these systems, and as a result are seldom established. This leaves the production management system isolated from other information sources. Therefore, this is considered to an important requirement and is addressed using a distributed web-services framework that will be discussed further below.

5.1.7 Differences between KanBIM and VisiLean

The main differentiating factor between VisiLean and KanBIM (Sacks et al., 2010) is that the predominant focus in VisiLean is on production planning and scheduling with a partial coverage of the control aspect, whereas in KanBIM the main focus is on the control workflow. Specifically, the following features are the ones, which are unique to VisiLean:

The Last Planner Workflow. This feature resulted from one of the most strategic decisions and provides a key differentiator between the KanBIM and VisiLean system. Where the KanBIM system took the planning workflow as a given and started from control perspective (in defining task maturity, readiness index and production status control), the VisiLean system focussed on the production planning and control workflow with the Last Planner™ system. As a

result, the following three planning components form the core part of the VisiLean system:

- i. Phase Planning
- ii. Look-Ahead planning
- iii. Weekly Planning and execution

Constraints Analysis and Management. Also, the constraints analysis and management feature, where each task is analysed and constraints added during the Look-ahead meeting, is unique to VisiLean. The constraints are then managed (they have to be removed before the execution week in order to “release” a task to the weekly schedule); this is a feature unique to VisiLean.

Resource Clash Detection. A unique resource clash detection function has been built in VisiLean, which identifies clashes between resources (i.e. if a resource has been assigned to multiple tasks at the same time). This is not present in the KanBIM system.

Project Administration, task definition and organisational structures. In VisiLean, it is possible to define organisational units at three different levels:

- i. Organisations (subcontractors, suppliers etc.)
- ii. Individuals (which belong to an organisation, or are independent)
- iii. Teams made up of individuals belonging to the same or different organisations.

Also, there were some features in KanBIM that were not implement in VisiLean from a strategic perspective. For example, KanBIM implements a feature called **maturity index**, which has been described above.

However, when designing Visilean, it was decided that a simple checklist and “yes” or “no” decision by humans (project team) would be better, as the probability index could mislead and create a false sense of security where the remaining, say 5% (unavailability of a resource) could result in a task completion becoming impossible (on schedule), and could result in “making do”.

In summary, it was informally agreed between KanBIM and VisiLean research teams that while VisiLean will focus on the planning and scheduling workflow, the KanBIM team will address the control workflow and visualisation of production status. During development, exchanges of information between research teams took place in terms of 3 virtual and 2 physical meetings (workshops). Overall, it can be stated that although both systems were designed separately, there was collaboration at a conceptual level, and consequently they complement each other well.

5.2 Choosing the Design Methodology

Based on the feedback gathered through focus group interviews and workshops and also through the literature as discussed above, a set of requirements was developed. As with any software development project, it is difficult to set very accurate or detailed requirements from the start. As understanding about the problem area evolves and a solution starts to take shape, further requirements are considered and initial requirements are evaluated.

The actual software development was carried out by another researcher (colleague of the author) working on the same project. The scope of the research reported in this thesis from software development perspective was the following:

- Define the conceptual requirements
- Specify the functional requirement
- Take part in the technology selection, i.e. software development platform, selection of the 3D viewing platform and the communication methods
- Continuous feedback in development and testing of the prototype
- Demonstration to the industry and research community, gathering feedback from partnering organisations, providing feedback to the developer

This section outlines the design process, how it was carried out and translated in software requirements, and the overall software architecture. Screenshots of the software prototype are provided to demonstrate how the functionalities were

realised, with high resolution screenshots in Appendix C. However, details of the actual programming process are not included in this discussion.

5.2.1 Development methodology

Traditional software development methods such as Waterfall Method of software development are criticised for their inefficiencies. This is mainly as the inherent shortcomings lead to unsatisfactory, unreliable and nonperforming products (Highsmith and Cockburn, 2001; Paetsch et al., 2003; Davis et al., 1988). Highsmith and Cockburn (2001) report on a recent study of more than 200 software development projects carried out, where the researchers couldn't find the original plans to measure the final product against. This is as the original plan was considered significantly out-of-date and the requirements changed significantly during the process to meet customer demand. One of the main reasons behind this is that the traditional methods put a significant emphasis on defining the complete set of requirements early and would not factor the change or variability in the process. The traditional methods can be seen as plan-based methods (similar to the "T" view in production), which emphasise "a rationalised, engineering-based approach" in which it is claimed that the problems are fully specifiable and that optimal and predictable solutions exist for each problem. The traditional methods emphasize on extensive planning, codified processes, and rigorous reuse to make the software develop in an efficient and predictable manner (Dybå and Dingsøy, 2008).

One of these traditional method is Requirement Engineering which is concerned with identifying, modelling, communicating and documenting the requirement for a system, and the contexts in which the system will be used. (Paetsch et al., 2003). The aim of Requirements Engineering is to help define what to build before system development starts in order to prevent rework, and is based on two major assumptions:

- The later mistakes are discovered, the more expensive it will be correct them (Beck, 1999)
- It is possible to determine a stable set of requirements before system design and implementation starts

The Requirements Engineering process consists of five main activities (Kotonya and Sommerville, 1997, Paetsch et al., 2003):

- Elicitation
- Analysis and negotiation
- Documentation
- Validation and
- Management

The traditional approaches can be likened to the “Transformation” or “T” view as discussed in Chapter 3 as in the manufacturing and construction sector. As in both cases, there is significant emphasis on advance detail planning, work breakdown and allocation and individual optimisation of tasks and work streams.

In the latest developments in software development methods, it is identified that the challenge is not in just accommodating change, but accounting for it and at the same time maintaining quality output. A relatively new software development paradigm, the Agile Software Development methods are a response to this challenge, where the strategy is to reduce the impact of change throughout the project (Highsmith and Cockburn, 2001). Paetsch et al. (2003) describe key differentiators of the Agile development methods:

- Agile methods are adaptive rather than predictive. With traditional methods, most of the software process is planned in detail over a large time frame. This works well if not much is changing (i.e. low requirements churn) and the application domain and software technologies are well understood by the development team. Agile methods are developed to adapt and thrive on frequent changes.
- Agile methods are people-oriented rather than process oriented. They rely on people’s expertise, competency and direct collaboration rather than on rigorous, document centric processes to produce high-quality software.

Dybå and Dingsøy (2008) also describe the main differences between traditional approaches mentioned above and agile software development processes as shown in Table 20.

Table 20. Main difference between traditional and agile development (Dybå and Dingsøy, 2008).

Aspect	Traditional Development	Agile Development
Fundamental Assumption	Systems are fully specifiable, predictable, and are built through meticulous and extensive planning	High-quality adaptive software is developed by small teams using the principles of continuous design improvement and testing based on rapid feedback and change
Management style	Command and control	Leadership and collaboration
Knowledge management	Explicit	Tacit
Communication	Formal	Informal
Development model	Lifecycle model (waterfall, spiral or some variation)	The evolutionary-delivery model
Desired organizational form/structure	Mechanistic (bureaucratic with high formalisation) aimed a large organisations	Organic (flexible and participative encouraging social action), aimed at small and medium organisations
Quality control	Heavy planning and strict control, late and heavy testing	Continuous control of requirements, design and solutions, continuous testing

There are a range of Agile Software Development methods, which are currently used. A summary of the most common methods has been provided in Appendix B.

As this is a research project where the requirements are bound to be changing based upon emerging evidence and user feedback, the flexibility and agility of the development system are crucial. With Scrum, it is possible to declare a product “done” whenever required, and also as the prototype can be demonstrated and implemented at any stage in a participating organisation to capture feedback. As a result, Scrum was selected as the development method during this research.

5.2.2 The Development Process

This research was carried out as a part of a larger research theme called “Seamless Delivery” within the Salford Centre for Research and Innovation (SCRI), under the work package “Collaborative Design, Planning and Construction”. There was a team of two researchers who developed VisiLean, where the scope of this research was to develop the concept, provide functional requirements, help with technology selection and assist in testing, demonstration and feedback gathering processes. The second member of the team carried out the programming activities, including designing database schema, object schema, prototype design and development. As a result, the actual programming activities are not presented in this thesis, as they were not within the scope of this research. The following development activities will be discussed as part of this research:

- Defining Functional Requirements
- Specifying the System
- Developing the System Architecture
- Iterative design of the System

Subsequently, Chapter 6 describes the evaluation process including the following aspects.

- Research Prototype Demonstrations
- Pilot project implementation
- Evaluating the system from the feedback

As mentioned above Scrum was selected as the development method. In Scrum, the practice is focussed around an iterative and incremental process skeleton, which is shown in Figure 27 (Schwaber, 2009). Here the lower circle represents the iteration of development activities, which occur one after another. Where the upper circle represents the daily inspection that occurs during that iteration, when the team members meet to inspect the progress and adapt to the changes. The main drivers behind the iteration are the functional requirements, and the cycle is repeated till the end of the project (or when the funding ceases).

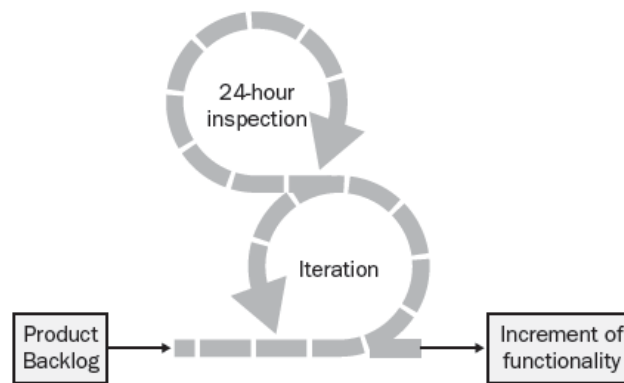


Figure 27. Scrum Skeleton (Schwaber, 2009).

5.2.2.1 Development Roles and Responsibilities

According to Schwaber (2009) there are three roles in Scrum:

- Product owner
- The Team and
- The Scrum Master

The product owner is responsible for securing initial and on-going funding for the project by developing the overarching concept, initial overall requirements, Return on Investment (ROI) objectives and release plans. The initial requirements is called the Product Backlog in Scrum, which helps prioritise the most valuable functionalities, and the requirements are prioritised frequently to correspond to the current situation. In developing VisiLean, as it was a research project, the task was to secure research funding and other resources (including personnel) to ensure the project can progress smoothly. The author was the Product Owner, who developed the initial requirements, and the product concept and secured the funding. As a Product Owner, the research candidate also engaged with the external and internal stakeholders to organise workshops, focus group interviews and meetings to gather feedback and capture requirements whenever necessary.

The team is responsible for developing the functionality, and also responsible for ascertaining the process to turn the Product Backlog into an increment of functionality within an iteration and managing their own work to do so. In Scrum the Teams are self-managing and organising and are also cross functional. As

mentioned above, the research team consisted of the author and another researcher, who carried out the programming duties. The team met almost daily to discuss the product backlog, and revise the priorities as necessary.

The Scrum Master is responsible for managing the Scrum process, and to ensure that it delivers the results expected from the project. As it was a very small project team, the role of Scrum master was not very relevant as both the members understood the process well and knew what had to be delivered. However, as the Product Owner, and responsible for the overall project, the author acted as the Scrum master.

5.3 Defining Functional Requirements for VisiLean

Defining functional requirements is one of the first steps following initial concept definition. Based on the requirements definition, system requirements are generated. For the sake of simplicity, these two steps are shown together in the discussion below along with the screenshots of the prototype. The functional requirements were defined through the following steps:

- Discussions with potential end users of system
- Study of previous production management system and literature (as reported in 5.1)
- Discussion among the development team

The following section lists the Product Requirements for VisiLean. Requirements are divided into the following sections:

- User Interface requirements. These are requirements for the user interface, which may be expressed as a list, as a narrative, or as images of screen mock-ups.
- Functional requirements. These are requirements written from the point of view of end users, usually expressed in narrative form.
- System and Integration requirements. These are detailed specifications describing the functions the system should be capable of doing.

5.3.1 User Interface Design

Designing the user interface is one of the most important tasks of system design, as the user interface shapes the experience of the user with the system. The user interface should shield the user from the complexity of the computing system underneath and make the overall experience rewarding. If the user interface is too complex the users may be put off due to a steep learning curve and amount of time taken to complete functions.

For a production management system, a simple and intuitive user interface is quite important due to the following reasons:

- Busy nature of construction professionals, especially due to a highly dynamic site environment and significant amount of information they have to deal with.
- Varying ICT skills as literacy (as such and also in terms of the familiarisation with computer systems) remains uneven in the industry.
- Highly complex systems may add to the variability of the process and have a negative impact of productivity, which will lead to its failure.

As a result, importance was placed on making the system simple and intuitive to use. The following process was followed while designing the user interface.

5.3.1.1 General User Interface

As the VisiLean system used an external BIM platform to link the product model (BIM) to the Lean Process, there were three possibilities. The first option was to have VisiLean as a plugin by building an external interface that will integrate with the BIM application. The second option was to build a self containing application that will access the product model (BIM) through an API (Application Programming Interface). Finally, the third option to build a product model visualisation interface (i.e. a BIM visualisation platform) from scratch. Here, to ensure simplicity and reduce the number of different interfaces (and windows) a user will have to deal with, it was decided that a self-contained application that accesses the BIM through an API was the best option.

Also, to minimise having windows that pop-up to support various system functions, a tabbed interface was chosen, with each collaborative planning

function namely phase, look-ahead and weekly will have a tab of its own along with the general administration and reporting functions. This will ensure uniformity in the user interface and improve the system workflow.

As the VisiLean system deploys a highly visual interface, the icons are also designed in a visual way so that the meaning of each icon becomes obvious by looking at it. For example, the equipment icon has a picture of a crane to provide a immediate visual feedback to the user. Also, in VisiLean colours are used to indicate the status of the task, activity or a phase. For example, in either the planning or BIM application the colour coding of a production item has the following meaning:

- Red depicts the production item as “not ready”
- Light Green, means it is ready for execution
- Dark Green – it is complete
- Blue – It is under process
- Yellow – work has stopped

When designing VisiLean, it was considered that a “Master-Detail” interface would be deployed, i.e. when a user makes a top level selection (for example the name of the project, a particular organisation, or a system user), relevant details will be displayed either at the bottom of the screen or on the right side, depending on the context. This makes it easier to navigate the system and access information, compared to the method where a new window is opened each time user wants to view the details of a certain item.

5.3.1.2 Process and Product Management in the same application window

One of the main considerations while devising the new production management system was the integration between the product and process management aspects. If these two representations are in two separate windows or in separate applications, it would not serve the original purpose of the application. Hence, it was decided that the main application would be split in two sections, where the product model (i.e. BIM) would be located on the right side, and the lean production management features would be situated on the left of the application.

Further details of the integration and visual feedback are provided in subsequent paragraphs.

5.3.1.3 Deploying a status window at the bottom

It is considered good practice to provide users, feedback about the actions they perform in the system; however, this should be done in a discreet and non-intrusive way so that it doesn't interfere with the main functions of the system. For this reason, a status bar has been designed, which is positioned at the bottom of the screen and provides feedback on user actions such as:

- The selected object (i.e. a project, a task etc.)
- Status of the last performed action (did it succeed, etc.)
- Progress bar, if there is an on-going process.

5.3.1.4 Familiar planning interface (to match leading planning applications)

As the VisiLean application is a production management application that implements collaborative planning features, there is a significant emphasis on planning and scheduling activities in the system. The collaborative planning functions extend the traditional Master Planning activities (such as the CPM), where applications such as Microsoft Project™ and Oracle Primavera Project Planner™ are used extensively within the industry. It was considered that while designing the planning and scheduling activities, the familiar planning interface should be deployed with additional features (such as constraints analysis and integration with BIM). By doing so, the users will quickly familiarise themselves with the activities and focus directly on the new features such as constraints analysis and BIM, hence reducing the time associated in learning a new system.

5.3.1.5 Touch friendly

With the developments in the mobile computing sector, especially with the devices such as tablets and smart phones, screens with multi-touch capabilities are becoming increasingly popular. Many such devices now offer functionalities such as “pinch to zoom in or zoom out”, rotating the picture or other screen artefact (such as a map) with two fingers, etc. Also, selecting and manipulating items with fingers rather than using the traditional keyboard and mouse is becoming commonplace for computer users.

As the newly designed production management system is intended to be used on the construction site where a computing skills of workers could vary greatly, it was considered that the system should be touch friendly. However, as initially the system will be deployed using a traditional computing platform (rather than a mobile platform), it was envisaged that a combination of traditional and touch friendly methods should be used. This would be achieved by using a system on a large screen such as a 42" plasma or LCD/LED screen and using a touch overlay. In VisiLean, the touch friendly features are also available on the BIM window where it is possible to Zoom, Select, Pan or Tilt the model using fingers.

In terms of the further development of planned mobile interfaces with VisiLean system, it is envisaged that an improved touch interface will be deployed that will enable multi-touch capabilities in the planning window and deploy features such as electronic Post-It™ notes, where each task is represented using a note and users can move these around during planning/scheduling sessions to change their sequence and immediately get a feedback of the change, similar to the manual collaborative planning exercise.

5.3.2 BIM/Product Visualisation Capability

Selection of a BIM platform and the product visualisation capability is one of the most important factors while designing the VisiLean system. There are a number of factors that were considered while selecting a platform, and are discussed below.

5.3.2.1 Acceptability of Major BIM File Formats

There is a wide range of BIM platforms in use currently, with majority of them using proprietary file formats, and much varied IFC (Industry Foundation Classes) compatibility. Any construction project will make use of a number of BIM models, including that of the Architect, Structural and HVAC. There will be tasks, which would be associated with each of these models; hence their availability in the production management system (VisiLean) is essential. This makes it highly important that any system chosen should be capable of accepting all major BIM file formats in use.

All major commercial and non-commercial (open source and research based) products were considered for integration in VisiLean from this point of view, along with other requirements listed below (and also the availability of an API to integrate it within the VisiLean application). Table 21 summarises the comparison between all the systems considered.

Table 21. Comparison between BIM systems considered for VisiLean.

BIM Platform Features	Autodesk Navisworks	Tekla Construction Management	Bentley Navigator	Tekla BIMSight	Vico Constructor
API capable of full integration	X	X			
Acceptability of major file formats	X	X	X	X	X
Navigation capabilities	X	X	X	X	X
4D capabilities	X	X	X		X
Embeddable BIM Viewer	X				

5.3.2.2 Navigation

Navigation of the model is one of the most basic features of any BIM application. From the point of view of a production management system the following capabilities are considered essential:

- Panning
- Zooming
- Rotating (Orbiting)
- Selecting components and
- Walking

As these are some of the most basic navigation functions, most applications reviewed implement these functions. It is also important that the navigation controls are available in the API (Application Programming Interface) so that they can be used within the VisiLean application. Figure 28 shows the BIM window in VisiLean, which implements these navigation functions as can be seen at the top of the screen.



Figure 28. The BIM Window in VisiLean.

5.3.2.3 Simulating Look-ahead and Weekly Planning (4D) capability

4D planning as described in Chapter 4, is a technique where the construction plan is linked to the Building Information Model and simulated against time to visualise the plan and carry out constructability analysis. This capability is also essential from a production management system perspective and hence desirable in the VisiLean system. While all the leading BIM systems can simulate the plan at a higher – Master Plan level, with VisiLean, the aim is to simulate the plan at the lower look-ahead and weekly (and even daily) levels. This provides an opportunity to carry out constructability analysis and process clash checking at a much finer level of resolution.

5.3.2.4 Quantity and Cost Take-off from model elements

One of the important aspects of having the Building Information Model available in the production management system is to have the product related information available on demand. In the early demonstrations to potential users, it was made clear that having quantity and cost related information was very important for the users. The potential workflow would be that when a task is linked to the corresponding BIM element, the quantity (and cost) information will be extracted automatically from the element and displayed with other task information. It should also be possible to keep a track of the actual consumption of resources, hence quantities and costs.

There was also a request from potential users to link Tender (Bid) quantities, costs and resources to the tasks, to compare with the actual and help generate reports such as Cost Value Reconciliation (CVR) automatically from the system.

5.3.3 Product and Process Integration Capability

In VisiLean, product and process integration is one of the most important aspects. It is here, that the production management process is integrated with the product model in a visual way, enabling graphical representation of where operations are physically located within a project and how they are progressing. This borrows from a lean production principle, namely 'visual management' (Tezel, 2010), whereby a number of visual devices are used to convey information about the workplace and to manage it. For example, the popup that relates to a task (a type of operation within VisiLean) has action buttons that allow users to change the status of the task by marking it as started or stopped etc. These buttons are inactive if the task's current status doesn't indicate that it is ready for execution. This feature is similar to the concept of a device known as poka-yoke, which roughly translates from the original Japanese as mistake-proof or fail-safe. The very act of placing a task popup adjacent to the model elements to which it relates, with those elements highlighted, is another visual management device in which the workplace becomes self describing: 'this is where to carry out task xyz, and these are the building elements involved'. The visual task representation is designed to make it easier for those in collaborative

planning meetings and those actually carrying out the work to see how the task relates to others in the same area and to record progress towards its completion.

The following describes how the product and process integration is achieved in VisiLean.

5.3.3.1 Linking tasks to model elements

Likewise in 4D planning, in VisiLean the tasks and sub-tasks are linked to their respective elements in the BIM model. This enables a spatial representation of the task in the model and helps visualise the task in a better way. Figure 28 shows the BIM window in VisiLean, with the Element Filters selection box expanded and also the Task Pop-up window in the centre of the screen. The following functionalities are available when the task and model element are linked:

- **Displaying process status on the model (individual tasks and phases):** Once linked, the element in BIM changes its colour to correspond to the colour that represents the task status (i.e. red, green, blue, etc.). Also, as shown in Figure 28, the status icon displaying task information is attached to the BIM element. By linking the process and product information in such a way, it is possible to visualise the status of the production at any given point in time, and also resolve any process clashes arising during execution. This also helps visualise the following information:
 - The organisation, or person responsible to carry out the task
 - Name of the task
 - Priority of the task
 - Status of the task
 - Any constraints linked to the task and their status
- **Zooming into selected elements:** Once the production item (a phase, task or an activity) and the BIM element are linked, each time the production item is selected, the system will automatically select and zoom into the corresponding BIM elements. The system will also make other elements transparent (up to a degree) so that the visualisation is easier.

- **Simulating a selection of tasks in 4D:** Once all the tasks and subtasks are linked to their corresponding elements, it would be possible to simulate the construction sequence in 4D through the BIM model.
- **Up-to-date product geometry, specifications and other technical information while defining the process:** When the tasks are linked, beside the quantity and cost information, all other relevant information regarding the geometry, specifications and specific work instruction that is linked to the BIM model should be made available to the task information.

5.3.3.2 Setting Task Status

Communication between workers during execution is critical, especially to ensure that the flow between activities is continuous and workers get notifications once the predecessor task is completed. In VisiLean, each task has four individual statuses, which are activated by pressing the corresponding button in the software, either in the software window or in the BIM window. Figure 29 displays the task status window as it is implemented in VisiLean.

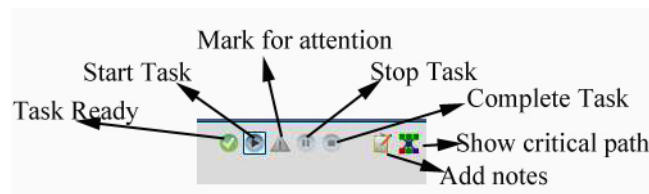


Figure 29. The Task Status window in VisiLean.

The task status update is possible from either the Weekly Planning module or from the status window on the BIM Model viewer. The statuses are described below.

- **Started:** Pressing the start button, starts the task and changes the colour of the task in plan window and also the corresponding element in the BIM window to blue.
- **Mark for Attention** (also see Andon section below): When this button is pressed, the relevant line manger (foreman, site manager or project manager), gets a notification of an imminent problem and attempts to rectify the situation before the work has to be stopped. The colour in both windows changes to yellow.

- **Stopped:** When pressing this button, the workers have to provide a reason why they are stopping the task. Once stopped, similar to the “mark for attention” button, the relevant line manager(s) get the notification so that they can respond accordingly to get the production back on line. At each weekly meeting, the reasons for stopping tasks are aggregated and analysed so that lessons can be learnt. The tasks marked with this status change their colour to red in both windows.
- **Complete:** Completing a task sets the colour to dark green and sends a signal to the next worker in line (if any) that they can now start the work. However, this notification will only be sent if all the other constraints for the next task are removed.
- **Add notes:** It is possible to add notes to tasks in VisiLean when changes are being made or to record any relevant information during execution.

5.3.3.3 Electronic Andon

Andon refers to a visual system that is used to highlight the status of production at any given point in time, and consists of a notice board showing different production areas and their individual statuses and control buttons (or other similar mechanisms) which workers use to indicate the current status. For example, in an apartment construction project, each floor could have three buttons:

- Green: production is progressing as normal
- Yellow: a problem is imminent
- Red: Production has been stopped

The main idea is that the person(s) responsible can then respond the problem before the work has to be stopped, and the communication happens efficiently, instead of worker(s) having to walk all the way to a managers cabin to notify of a problem.

In VisiLean, the equivalent of physical Andon board is conceptualised. Each task has a corresponding button to flag imminent problems. Once pressed the relevant line manager is sent a notification so that appropriate actions can be taken. Similarly to the physical Andon notice board, a large screen in the main

office could be installed to show the status of the production at any given point in time (with colour coded model overlaid with task status information).

5.4 Specifying the VisiLean System

In the following, the parts of VisiLean system are specified and discussed. Also, the sequence in which they were tackled and relevant screenshots from the prototype are provided.

5.4.1 Project Administration

As production management is an information intensive process, a significant amount of information has to be managed in order for it to function smoothly. The Project Administration section handles all the information associated with the project that is relevant to the production management aspect. This essentially means the definition and management of Project Resources, which might include Personnel, Information, Equipment, Materials, Components and the Spaces defined within and/or around the proposed structure (these are the terms used in VisiLean and differentiated with a title case). In essence, information that is necessary to carry out constraints analysis during production management.

As most such information resides in electronic/computer systems within stakeholder organisations, the ideal way to manage it would be to integrate such information directly within VisiLean to minimise manual data entry. However, due to the lack of live sample data and limited access to construction information systems within partner companies, in the first iteration of the software, all such Resources have to be manually input to the system by users. The information required includes name and description for the Resource, when it is anticipated that it will be delivered to the project, whether or not it is available at any given moment in the project and what task, if any, within the project a Resource is currently assigned to.

In future development of VisiLean, it is envisaged that a large proportion of this information will be derived from third party data systems via web service interfaces designed to extract the relevant information from those systems. Further, whilst at present the anticipated and actual delivery dates for a resource

are input and updated manually, it is intended that where possible this should be achieved via a live or semi—live link to external systems such that information coming from product suppliers etc. is automatically incorporated into VisiLean ensuring that it is always up to date. Such a link would be implemented using web services, both the WSDL/SOAP (W3C 2001, 2007) and REST (Fielding 2000) varieties as necessary for integration of external systems into the workflow of the project. Further discussion about web services and database management can be found under the Section 5.5.

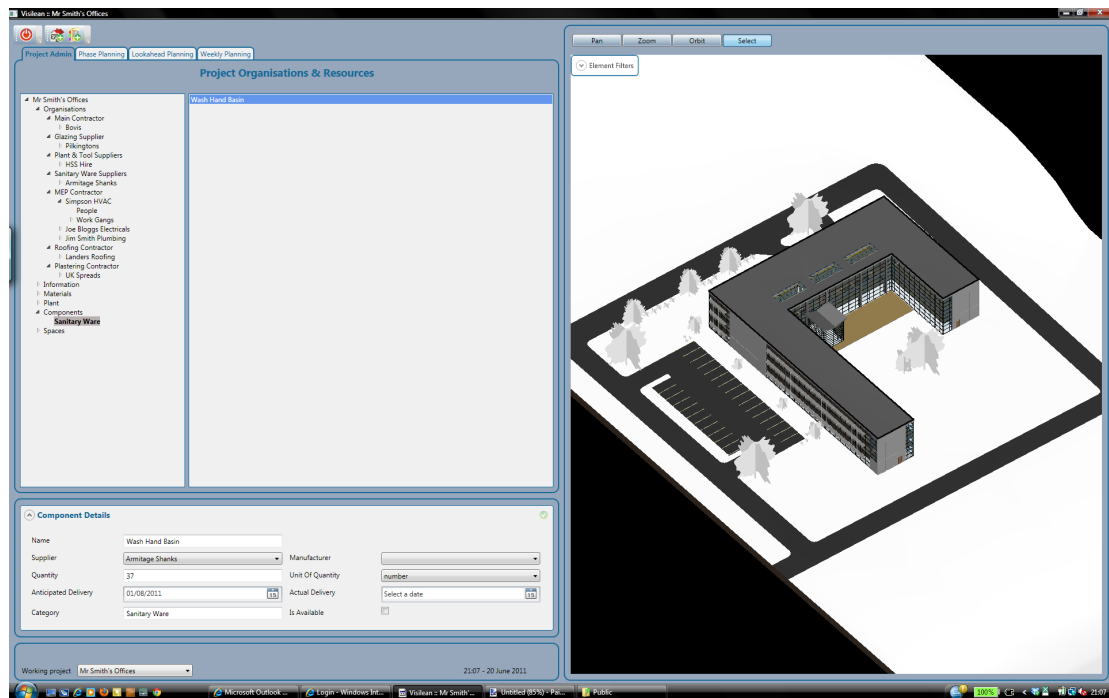


Figure 30. Project Administration Screenshot.

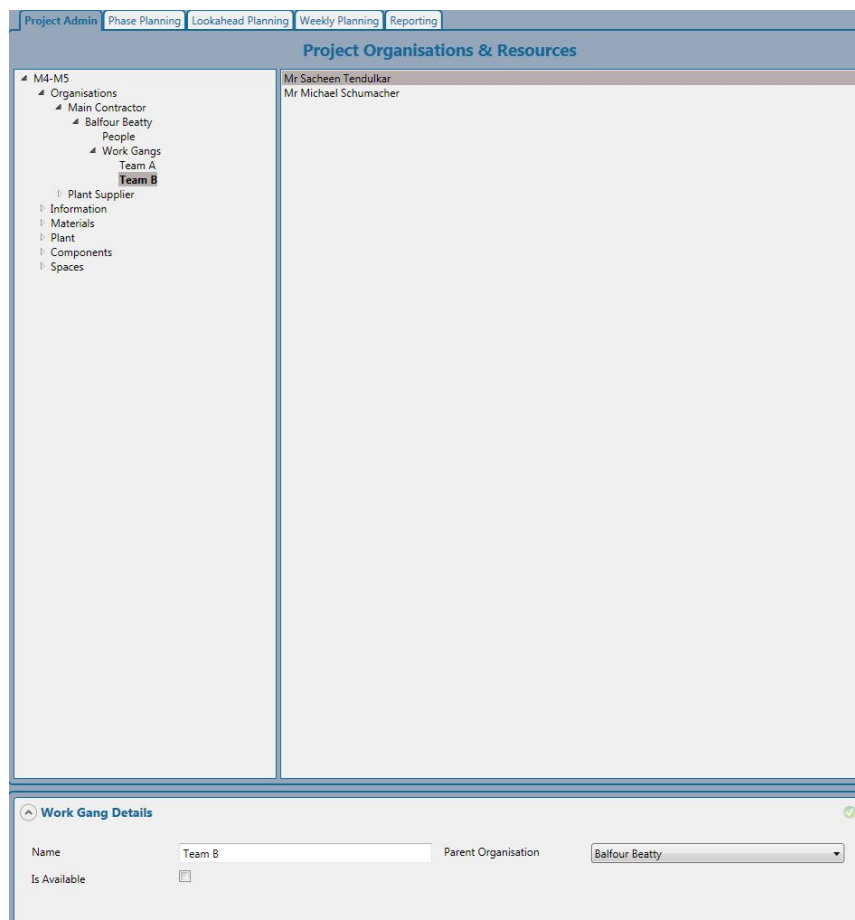


Figure 31. Adding Organisation and Teams in VisiLean.

Figure 30 and Figure 31 show the screenshot of the Project Administration screen as developed in VisiLean. In Figure 31 the screen shows members of a team that belongs within a particular organisation. This demonstrates the organisation hierarchy (i.e. organisation, people and teams). Once an organisation is created within VisiLean and people added to that organisation, the team creation window will show the available people to choose from in the Team Selection dialog box. Table 22 describes the functional specifications for the project administration module. The specifications are described throughout the document using this format. The requirement, and the system specification in how that requirement will be satisfied are provided, along with which phase/release it will be developed under.

Table 22. Project Administration Specifications in VisiLean.

Requirement	Specifications
Project	
Create Project	<ol style="list-style-type: none"> 1. Create a new project. On clicking on New Project, a screen should pop-up asking the user to add all the details for the new Project. The same could be achieved using the details area rather than a popup. This applies for all new items that follow (materials, people etc.) 2. Define details of the project such as Name, Start Date, End Date and other details. <p>The Created / Imported Project needs to be saved separately as the Base line Project so that comparisons can be made with this Project while Reporting</p>
Update Project	<ol style="list-style-type: none"> 1. Update the details of the project. 2. On selecting a Project from the tree view displayed in the left panel of the screen, all the details of the Project are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Project	Delete Project.
Import Project	Project will be imported from Primavera or MS Project
View Project	<ol style="list-style-type: none"> 1. View details of an existing project. 2. All the Projects are shown in a Tree view in the left panel on the screen. User can click on the Project for which he wants to view the details. System will display the details of the selected Project in a window at the bottom of the screen.
Organization	
Create Organization	<ol style="list-style-type: none"> 1. Create a New Organization. On clicking on New Organization, a screen should pop-up asking the user to add all the details for the new Organization. 2. Define details of the Organization such as Name, Address, Contact Person, Contact Details, Type of Organization, Type of Work etc.
Update	1. Update Details of the Organization.

Requirement	Specifications
Organization	2. On selecting an Organization from the tree view displayed in the left panel of the screen, all the details of the Organization are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Organization	1. Delete Organization.
View Organization	1. View the Details of the Organization. 2. All the Organizations are shown in a Tree view in the left panel on the screen. User can click on the Organization for which he wants to view the details. System will display the details of the selected Organization in a window at the bottom of the screen.
People/Person	
Create Person	1. Create a New Person. On clicking on New Person, a screen should pop-up asking the user to add all the details for the new Person. 2. Define the details of the created Person such as Name, Contact Details etc. 3. Each person will have a Login Id and Password
Link Person to an Organization	A Person can be linked to an Organization. User should be able to select an Organization from the dropdown on the pop-up screen for New Person.
Assign a Project Role to a Person	1. A person can be assigned a Project Role. User should be able to select the Project Role from the dropdown on the pop-up screen for New Person.
Update User	1. Update the details of the already created Person. 2. On selecting a Person from the tree view displayed in the left panel of the screen, all the details of the Person are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove User	1. Delete Person.
View User Details	1. View the details of the Person. 2. All the Person defined under an Organization are shown in a Tree view under the heading Organization Name – People – Person Name in the left panel on the screen. User can click on the Person for which he wants to view the details. System will display the details of the selected Person in a window at the bottom of the screen.
Work Gangs	
Create Work Gang	1. Create a New Work Gang. On clicking on New Work Gang, a screen should pop-up asking the user to add all the details for the new Work Gang. 2. Define the details of the Work Gang.
Update Work Gang	1. Update the details of work gang. 2. On selecting a Work Gang from the tree view displayed in the left panel of the screen, all the details of the Person are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Work Gang	Delete Work Gang
View Work Gang	1. View the details of the work gang.

Requirement	Specifications
	2. All the Work Gangs defined under an Organization are shown in a Tree view under the heading Organization Name – Work Gang – Work Gang Name in the left panel on the screen. User can click on the Work Gang for which he wants to view the details. System will display the details of the selected Work Gang in a window at the bottom of the screen.
Project Role	
Create Project Role	1. Create a new project role. On clicking on Create Project Role, a screen should pop-up asking the user to add all the details for the new Project Role. 2. Define the details of project role
Update Project Role	Update the details of Project Role
Remove Project Role	Delete Project Role
View Project Role Information	View the details of Project Role
Create Information	1. Create New Information. On clicking on New Information, a screen should pop-up asking the user to add all the details for the new Information. 2. Define details in the information such as type of information, description etc. 3. User should also be allowed to attach document with the information.
Update Information	1. Update details in the information 2. On selecting Information from the tree view displayed in the left panel of the screen, all the details of the Information are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Information	Delete information.
View Information	1. View the details of the information 2. All the Information defined under a Project is shown in a Tree view under the heading Project Name – Information – Information Name in the left panel on the screen. User can click on the Information Name for which he wants to view the details. System will display the details of the selected Information in a window at the bottom of the screen.
Materials	
Create Material	1. Create New Material. On clicking on New Material, a screen should pop-up asking the user to add all the details for the new Material. 2. Define the attributes of the material like Name, Supplier, Quantity, UoM Anticipated Delivery Date, Actual Delivery Date etc.
Update Material	1. Update the details of the Material. 2. On selecting a Material from the tree view displayed in the left panel of the screen, all the details of the Material are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Material	Delete Material for the project.

Requirement	Specifications
View Material	<ol style="list-style-type: none"> 1. View the details of the Material. 2. All the Materials defined under a Project is shown in a Tree view under the heading Project Name – Material – Material Name in the left panel on the screen. User can click on the Material Name for which he wants to view the details. System will display the details of the selected Material in a window at the bottom of the screen.
Plant	
Create Plant	<ol style="list-style-type: none"> 1. Create New Plant. On clicking on New Plant, a screen should pop-up asking the user to add all the details for the new Plant. 2. Define the details of the plant such as Name, ID, Supplier, Manufacturer, Quantity, Category etc.
Update Plant	<ol style="list-style-type: none"> 1. Update the details of the Plant. 2. On selecting a Plant from the tree view displayed in the left panel of the screen, all the details of the Plant are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Plant	Delete Plant.
View Plant	<ol style="list-style-type: none"> 1. View the details of the Plant. 2. All the Plants defined under a Project are shown in a Tree view under the heading Project Name – Plant – Plant Name in the left panel on the screen. User can click on the Plant Name for which he wants to view the details. System will display the details of the selected Plant in a window at the bottom of the screen.
Components	
Create Component	<ol style="list-style-type: none"> 1. Create new component. On clicking on New Component, a screen should pop-up asking the user to add all the details for the new Component. 2. Define attributes of the component such as Name, Supplier, Manufacturer, Quantity, Anticipated Delivery, Actual Delivery, Category etc.
Update Component	<ol style="list-style-type: none"> 1. Update the attributes of the component. 2. On selecting a Component from the tree view displayed in the left panel of the screen, all the details of the Component are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.
Remove Component	Remove component
View Component	<ol style="list-style-type: none"> 1. View the details of the component. 2. All the Components defined under a Project are shown in a Tree view under the heading Project Name – Components – Component Name in the left panel on the screen. User can click on the Component Name for which he wants to view the details. System will display the details of the selected Component in a window at the bottom of the screen.
Spaces	
Create Space	<ol style="list-style-type: none"> 1. Create a New Space. On clicking on New Space, a screen should pop-up asking the user to add all the details for the new Space. <p>It is anticipated that the spaces will be defined already in the 3D</p>

Requirement	Specifications
	<p>model. Also, there is a possibility of having locations defined (i.e. project divided in zones rather than using spaces). Having such locations is a common practice on construction projects. This needs further investigation and validation from the actual users of the software. For the time being it is left to the user to define spaces in VisiLean and connect to the task (which is then connected to a 3D model).</p> <p>2. Define details of the space such as Name, ID and other information.</p>
Update Space	<p>1. Update the details of the space.</p> <p>2. On selecting a Space from the tree view displayed in the left panel of the screen, all the details of the Space are displayed in a window at the bottom of the screen. Some of these details will be editable. User can edit the details on this screen.</p>
Remove Space	Delete Space from Project
View Space	<p>1. View the details of the space.</p> <p>2. All the Spaces defined under a Project are shown in a Tree view under the heading Project Name – Space – Space Name in the left panel on the screen. User can click on the Space Name for which he wants to view the details. System will display the details of the selected Space in a window at the bottom of the screen.</p>

5.4.2 The Planning Process in VisiLean

The planning process is the core part of the application and is designed to support the Last Planner™ workflow of planning. It was anticipated (and feedback received to the same effect) that the contractors would continue using their respective planning applications such as Microsoft™ Project or Primavera™ Project Planner. The VisiLean application aims to support the planning workflow that stems from Phase Planning onwards. To ensure minimal rework, a facility to import existing plans from above mentioned applications has been recommended. The planning process in VisiLean consists of the following modules:

- Phase Planning
- Look-ahead Planning
- Weekly Commitment Planning

One of the most important aspects of the Last Planner™ system is the collaborative planning and scheduling approach it facilitates among the site team. A number of studies have suggested that this particular aspect of collaborative planning increases trust and improves the reliability of planning to a great extent. During initial discussions with the industry practitioners who had

prior experience in implementing the Last Planner™ system, it emerged that they strongly recommended keeping this collaboration aspect “as is” and in a “face-to-face” setting. Although it is possible to replace the physical meeting to a virtual meeting, this request was acknowledged in VisiLean research, and hence the system was not designed to replace this “face-to-face” collaboration, rather to support it.

Through the use of VisiLean system, the collaborative planning process is strengthened by simultaneous viewing (by the Last Planners) of the Phase, Look-ahead and Weekly plans, and the Building Information Model through a projected screen or a large television on site. During these meetings, the Last Planners will negotiate with each other the sequencing and other execution related issues, and also agree who will bear the responsibility in removal of constraints. As shown in Figure 4 in Appendix C, the task filtering helps to select relevant tasks during the planning sessions, so that certain actions can be taken such as addition of constraints or releasing the task to the execution week, etc. The system records the person (or team) responsible for managing the task in the Look-ahead and Weekly plans. It is envisaged that In a future version of VisiLean, a distributed access system will enable subcontractors to login and manage their own part of the production plan and constraints.

The Phase, Look-ahead and Weekly planning workflow is explained in detail in Section 5.4.2.1, 5.4.2.2 and 5.4.2.3, respectively.

The activity tab area supports a process of work planning from initial phase definition through collaborative sessions to define look-ahead and weekly plans based on current information regarding resource availability and defined priorities for tasks. The application does not automatically select tasks which should appear in look-ahead and weekly plans beyond filtering to those which fall wholly or partly within the requisite date ranges, the final decisions being left to those involved in the collaborative planning meetings.

The BIM model viewer shows graphically, which model elements are related to which tasks in the project plan. This is achieved by selecting the relevant model elements in the viewer window, which brings a popup window with the name of the task or sub-task related to those elements. The popup window also displays a

description for the task, its status, the project parties responsible for the task and the actions that are possible for the task such as start, stop and mark complete. These windows will eventually display a broader range of information about prerequisites for the task. The functional requirements, specifications and screenshots for each of these modules are provided below.

5.4.2.1 Phase Planning

The phase planning in VisiLean provides equivalent functionality to that of “reverse phase scheduling” as in the Last Planner™ process. The main purpose of “reverse phase scheduling” is to bring together the whole project team and work backwards to reach an agreement on the overall project sequence for a chosen duration (typically 3-6 months).

In VisiLean the overall structure of the project plan can be defined down to any level of activity, i.e. a user can define phases, tasks, sub-tasks to the n^{th} level as an activity. Alternatively activities can be added directly in the subsequent look-ahead planning interface as and when they are identified. It is anticipated that at this stage a Master Plan will be imported from an existing application. While importing the plan, existing relationships between tasks will be preserved. To begin with, mono-directional input is provided for (i.e. from external applications to VisiLean), however, it is recommended that in future versions a multi-directional link should be provided to ensure that the changes in project status are reflected in the Master Plan. Figure 32 and Figure 33 show the phase planning screen in the VisiLean prototype, where the tasks coloured in red (also selected in BIM) are the “not ready” tasks as the constraints haven’t been removed, whereas the light green tasks are ready, dark green tasks are complete and tasks coloured blue have started. Table 23 describes the system specifications for phase planning module.

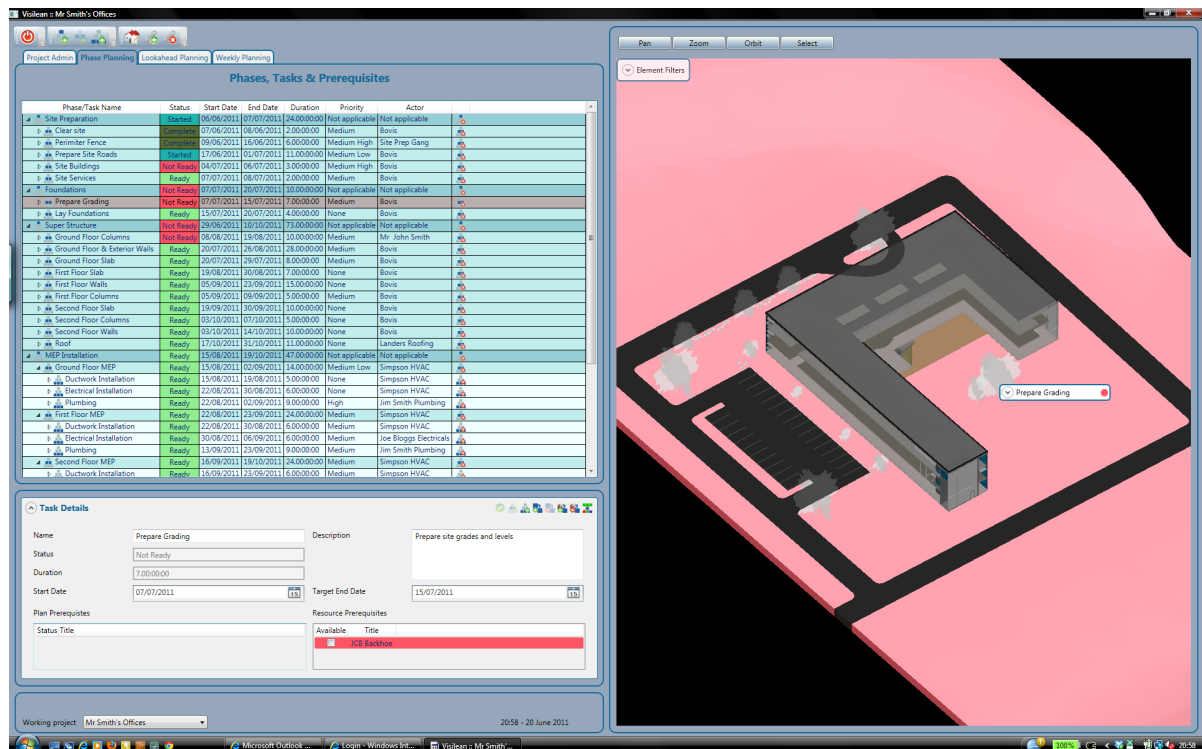


Figure 32. Phase Planning in VisiLean.

Project Admin Phase Planning Lookahead Planning Weekly Planning Reporting

Phases, Tasks & Prerequisites

Activity Name	Status	Start Date	End Date	Duration	Priority	Actor
Install Comms Ducts	Ready	07/01/2013	15/02/2013	30:00:00:00	None	Balfour Beatty
COMMS_DUCT_P100x1_EI001	Ready	07/01/2013	07/02/2013	24:00:00:00	Medium	Balfour Beatty
COMMS_MDUCT_P100x1_AI01	Ready	08/01/2013	08/01/2013	1:00:00:00	Medium	Team A
COMMS_MDUCT_P100x1_AI01	Ready	08/01/2013	08/01/2013	1:00:00:00	Medium	Team A
COMMS_MDUCT_P100x1_AI00	Ready	08/01/2013	08/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P100x2_AI015	Ready	08/01/2013	08/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P100x2_AI001	Ready	08/01/2013	08/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P100x2_AI010	Ready	08/01/2013	08/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P100x1_E4180	Ready	09/01/2013	09/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P100x1_A4756	Ready	10/01/2013	10/01/2013	1:00:00:00	Medium	Team A
COMMS_MDUCT_P100x1_A476	Ready	10/01/2013	10/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P100x1_E4185	Ready	10/01/2013	10/01/2013	1:00:00:00	Medium	Team A
COMMS_MDUCT_P100x1_A475	Ready	10/01/2013	10/01/2013	1:00:00:00	Medium	Team A
COMMS_DUCT_P50x1_M48_48	Ready	10/01/2013	10/01/2013	1:00:00:00	Medium	Team B
COMMS_DUCT_P100x4_A4756	Ready	10/01/2013	10/01/2013	1:00:00:00	Medium	Team B
COMMS_MDUCT_P100x1_A50	Ready	14/01/2013	15/02/2013	25:00:00:00	Medium	Team B
COMMS_MDUCT_P100x1_A50	Ready	16/01/2013	17/01/2013	2:00:00:00	Medium	Team B
COMMS_MDUCT_P100x1_AI30	Ready	18/01/2013	18/01/2013	1:00:00:00	Medium	Team B
COMMS_MDUCT_P100x1_AI29	Ready	18/01/2013	18/01/2013	1:00:00:00	Medium	Team B

Activity Details

Name: COMMS_DUCT_P100x1_EI001_AI005 Description: COMMS_DUCT_P100x1_EI001_AI005

Status: Ready

Duration: 24:00:00:00

Start Date: 07/01/2013

Target End Date: 07/02/2013

Actual Start Date:

Actual End Date:

Responsible Actor: Balfour Beatty

Constraints:

Name
Comms Installation Instrument

Working project: M4-M5 00:24 - 12 January 2013

Figure 33. Phase Planning Tasks Window.

Table 23. Phase Planning Specifications in VisiLean.

Requirement	Specifications
Create Phase	<ol style="list-style-type: none"> 1. Create a new Phase 2. Enter the Details of the phase such as Name, Description, Start Date, Organisation/Actor, and Target Completion Date. Based on the Start Date and Target Completion Date, system will calculate the duration and display as a field.
Update Phase	<ol style="list-style-type: none"> 1. Update the details of the Phase. 2. On selecting a Phase from the table displaying the phases, all the details of the Phase are displayed in a window at the bottom of the screen. The details include all the information that was defined at the time of creation of the Phase. Some of the information displayed will be editable. User can update the details on this screen.
Remove Phase	Delete the phase from the project.

Requirement	Specifications
View Phase	<p>1.View the Details of the phase. All the Phases defined are shown in a tabular form on the main screen. All the tasks defined under a Phase are displayed in the hierarchal tree format. Status of the Phase is also displayed along with the Phase details.</p> <p>2. Status is “Started” if the Start Date of the Phase is less than or equal to the System Date.</p> <p>If all the prerequisites for the phase are available, system marks the status of the Phase as “Ready”.</p> <p>If one or more prerequisites for the phase are not available, system marks the status of the Phase as “Not Ready”.</p> <p>If all the tasks under the phase have been completed, the status of the Phase is marked as “Complete”.</p> <p>3. On selecting a Phase, all the details of the Phase are displayed in a window at the bottom of the screen. The details include all the information that was defined at the time of creation of the Phase. Some of the information displayed will be editable.</p>
Task	
Create Task	<p>1. Create a new Task.</p> <p>2. Define the details of the task such as Name, Description, Start Date, Target Completion Date and Priority. Duration should be calculated and displayed based on the start date and Target Completion Date.</p>
Link Task to Parent Phase	The task should be able to be linked to a Phase. Parent phase for the task can be selected using a dropdown.
Assign Responsible Actor for the Task	User should be able to assign an actor to the task that will be responsible for the execution of task. The actor can be a Person, a Work Gang, An Organization or any other unit. The task should be first assigned to an Organization Representative who will be a primary contact for the Project Manager as well as the Persons working in that Organization.
Update Task	<p>1. Update the details of the task.</p> <p>2. On selecting a Task from the table displaying the phases/tasks, all the details of the Task are displayed in a window at the bottom of the screen. The details include all the information that was defined at the time of creation of the Task. Some of the information displayed will be editable. User can update the details on this screen.</p> <p>3. In Phase 1 the Task will have only ‘Started’ and ‘Complete’ states once they are started. There will be no partial % complete states.</p> <p>4. If a task in Primavera or MS Project is 0% complete, then after importing the task into VisiLean, the task status should be “Ready”. Only if there are no incomplete preceding tasks (prerequisites). In the event that such incomplete preceding tasks exist, then the status would be “Not Ready”</p> <p>5. If a task in Primavera or MS Project is 1 – 99% complete, then after importing into VisiLean, the task status should be “Started”.</p> <p>6. If a task in Primavera or MS Project is 100% complete, then after importing into VisiLean, the task status should be “Complete”.</p>
Remove Task	Delete task from the Project/Phase.
View Task	1. View the Details of the task. All the tasks defined under a Phase are shown in a tabular form on the main screen. Status of the Task is also displayed along with the Task details.

Requirement	Specifications
	2. On selecting a Task, all the details of the Task are displayed in a window at the bottom of the screen. The details include all the information that was defined at the time of creation of the Task. Some of the information displayed will be editable.
Element Filters	
Apply Element Filters to view specific elements	<ol style="list-style-type: none"> 1. User should be able to select an element in the model view using the element filters. It should display the elements in hierarchal view so that it is easy for user to search for the element. 2. Once the user selects an element filter, system should display the selected element in model view.
Clear Filters	1. User should be able to clear all applied filters using the “Clear Filter” button. On clicking “Clear Filter” button, all the filters should be removed and model view should display the original model.
Plan Prerequisites	
Create Plan Prerequisite for a Task	<ol style="list-style-type: none"> 1. User should be able to assign one task as a prerequisite for another task. On selecting a task and clicking on Plan Prerequisites, a popup should be displayed which asks the user to select prerequisite for the selected task. User can assign multiple tasks in a phase as a prerequisite for the selected task. 2. In Phase 2 and beyond it is envisaged that the Tasks can be linked to one another with multiple Relationships (with lags) viz (FS-Finish to Start, SS-Start to Start, FF-Finish to Finish and SF-Start to Finish. In Phase 1 defining a Prerequisite amounts to creating a FS relationship 3. In current Phase if the Project and Tasks are imported from Primavera or MS Project, then it is likely that the relationship info may flow in. There is a need to investigate further as to how the imported Relationships will be handled
Resource Prerequisites	
Add resource constraints	<ol style="list-style-type: none"> 1. Add resource constraints to tasks. Resource constraints are created first in the Project Administration tab and are made available in the Phase and Look-Ahead planning tab. 2. Resource constraints could be any of the following: Material, Equipment, Space, Actors (Organisation, Team or individuals), and Information. 3. Also, assigning resource constraint removal responsibility to actors.

5.4.2.2 Look-Ahead Planning

As discussed in the Chapter 4, the purpose of look-ahead planning is to create a workable backlog of “ready” tasks, which are free of constraints. It is a highly collaborative process where all relevant stakeholders take part in the meeting, and analyse the tasks in hand to identify all major constraints, assign responsibilities for their removal and make promises to each other that the constraints will be removed in time. In this meeting the aspects of collaboration,

constraints analysis, and understanding the sequence and where tasks are to be performed are important.

In VisiLean, the Look-Ahead planning function offers the capability to pull the tasks from the phase plan, where the look-ahead window is configurable on a project wide basis, with a default value of 3 weeks. The tasks selectable from the phase plan are filtered by date, such that only those falling within the look-ahead window are available. If tasks have not yet been defined, it is also possible to create new ones at this stage and assign them to an existing phase whose duration coincides with all or part of the look-ahead window. As with other tabs, the selected item in the Look-Ahead tab the task details are displayed in the bottom (beneath the activity tab area).

The Look-Ahead workflow within VisiLean is presented in Figure 34.

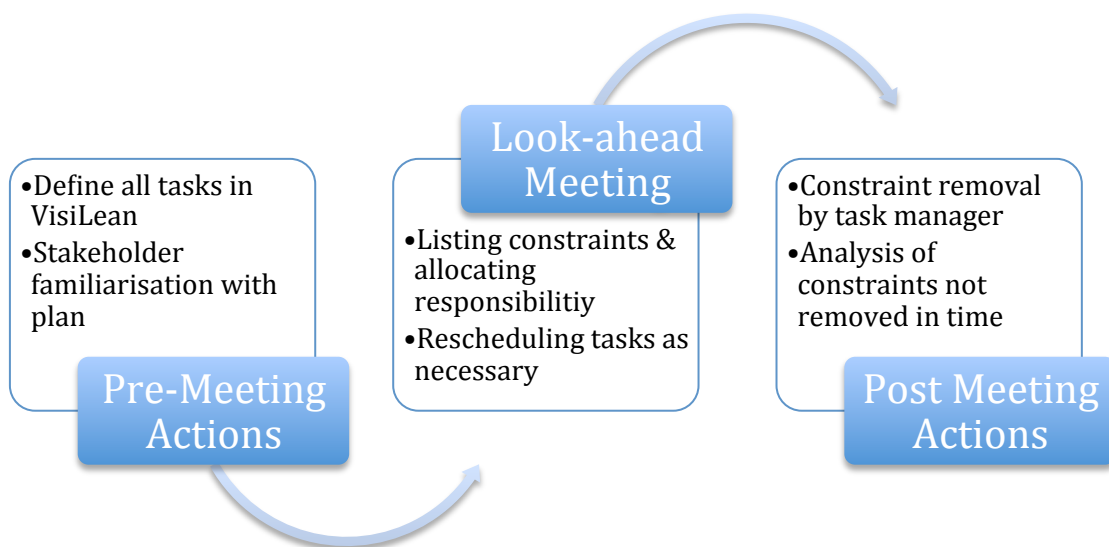


Figure 34. Look-ahead planning workflow in VisiLean.

- **Pre-meeting actions:** The VisiLean coordinator ensures that all tasks are defined and are linked to their respective elements in the BIM model
 - All project stakeholders do their “homework” to ensure that they are familiar with what is being planned and get an update on the constraints

- **Collaborative Meeting:** The VisiLean Coordinator drives the system during the meeting to dropdown the tasks from the phase plan into the Look-Ahead plan and the constraints are added/listed by subcontractors. For each task selected, the VisiLean BIM window will show the respective information. The following actions are taken during the meeting:
 - The constraints are analysed and added to individual tasks.
 - The task manager commit that they would be removed before the week of execution.
 - Any decisions taken to remove certain tasks from the Look-Ahead window (if they can't be made ready in time) are also recorded and such tasks are dropped back to the phase plan to be rescheduled.
- **Follow up:** Following the Look-Ahead meeting, each actor who has been assigned the responsibility of removing the constraints, accesses the system to tick the box next to each constraint to indicate that it has been removed/resolved. Once all constraints are resolved a task becomes "ready" and can be released to the weekly plan. Any constraints that have not been removed will have to be analysed and the reasons recorded.

One of the more important follow-up actions in look-ahead planning in VisiLean is the 'Release to weekly' action button. This action is only available for a given task once all the prerequisites are met (constraints removed) and it is ready to start. Initiating this action adds the selected task to the weekly plan in preparation. Figure 35 shows the screenshot of the look-ahead planning window in VisiLean and Table 24 provides a description of the system specifications for the look-ahead module in VisiLean.

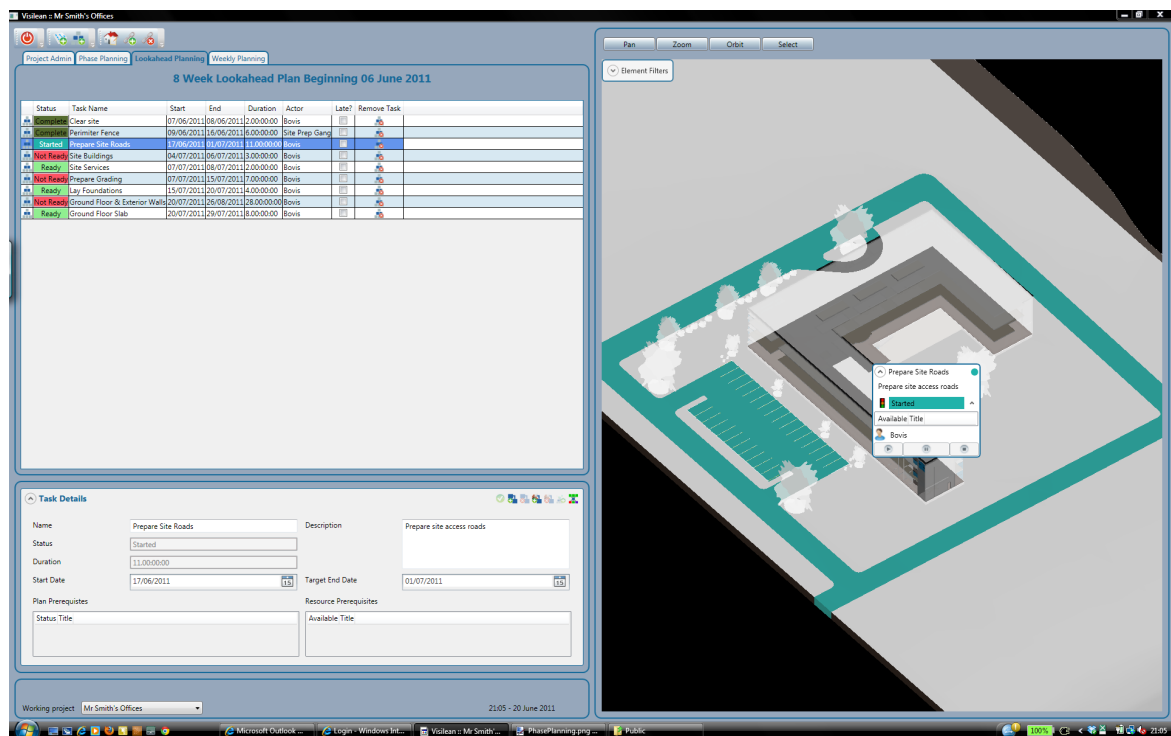


Figure 35. Look-ahead Planning in VisiLean.



Figure 36. Look-ahead Planning Window in VisiLean.

Activity Details

Name: COMMS_DUCT_P100x1_EI001_AI005

Status: Ready

Duration: 24.00:00:00

Start Date: 07/01/2013

Target End Date: 07/02/2013

Actual Start Date:

Actual End Date:

Responsible Actor: Balfour Beatty

Description: COMMS_DUCT_P100x1_EI001_AI005

Constraints:

Name
Comms Installation Instrument

Figure 37. Task Detail Window in Look-ahead Planning.

Table 24. Look-ahead Planning specifications in VisiLean.

Requirement	Specifications
Select Tasks for Look-ahead Planning	<p>1. User should be able to pull tasks from the phase plan and schedule them in the look-ahead window. When user clicks on “Select Tasks”, a window should pop-up, which displays all the phases and tasks under the project. User should be able to filter these tasks based on start date and end date, space name, organization name, role name etc. User can multi-select these tasks to pull them in the look-ahead planning.</p> <p>2. Also, system will automatically populate all the tasks falling in the look-ahead window and will give user an option to deselect tasks if he wants to.</p>
Task released to weekly Planning	User should be able to move the task from look-ahead planning to weekly planning. An action button should be provided to move the selected task from look-ahead planning window to weekly planning window. The button will be enabled only for tasks with a “Ready” status.
Task to be marked as Late	<p>1. System should automatically mark the Task as late if the task has not been completed till the Target End Date. This should be a display field and not a checkbox. Currently the prototype has a checkbox for marking the task as late.</p> <p>2. There should be also a facility to enter new Start or End dates or both</p> <p>3. Depending on the newly enter dates the Task can/will be moved to relevant week or look ahead plan</p>

5.4.2.3 Weekly/Commitment Planning

The weekly planning meeting, which is also known as the “commitment” planning meeting, is organised to ensure that only the constraint free tasks are selected for execution during next week, and that all stakeholders commit to the tasks selected and the sequence of operation. During this meeting, the following workflow is followed:

- **Pre-Meeting:** All actors responsible for removal of constraints (during the Look-Ahead window) would have addressed the constraints prior to

the meeting. The tasks would have been dropped to the weekly plan by clicking the “release to weekly” button once the constraints have been removed. For the tasks where the constraints haven’t been removed, explanation would have been provided, and they will be put back in the pool for rescheduling.

- **During meeting:** The weekly work plan would automatically be populated and the VisiLean coordinator would go through each subcontractor’s tasks to ensure that all the parties are satisfied with the sequence and are committed to it. The BIM window will visually display the status of each task, and hence help visualise the sequence of planned tasks. Any changes in sequence needed would be done at this stage. Also, task priorities (if not set already at the Look-ahead meeting) are set by the project manager or collectively by the group. These priorities help task managers select the tasks for execution during the week.
- **Post-meeting:** Each stakeholder is responsible to execute their tasks in order of set priority. There are four buttons provided to each task, start, mark for attention, pause/stop and complete. Once the task is complete, the team responsible for starting the next task in sequence gets a notification.

The weekly planning tab is where tasks for the current week (the executing plan) or the coming week (the plan in preparation) are listed. There are buttons provided to navigate between the current and in preparation plans, and also previous plans which are archived for future reference. There is a filter function that allows users to show only certain tasks and sub-tasks assigned to a given actor or between certain dates for example. The details area once again displays detailed information for the selected item (task or sub-task) in the weekly planning panel. The actions available for the selected task will now include start, mark for attention, stop and complete, and pressing these buttons will thereby update the task status, which will be reflected in the BIM model viewer overlay for the item. Also, if the item is not completed by the target completion date, the option to define a reason for variance from plan becomes available.

Users can select from a number of categories for the variance and provide extra descriptive detail as to the exact nature of the variance.

It should be noted that currently, any task assigned to the weekly plan must have a duration that fits within the week – this may require further subdivision of tasks into smaller units to meet this rule either automatically or by informing the user and allowing them to do it.

Figure 38 shows a screenshot of the weekly planning window in VisiLean and Table 25 describes the system specifications and the release schedule.

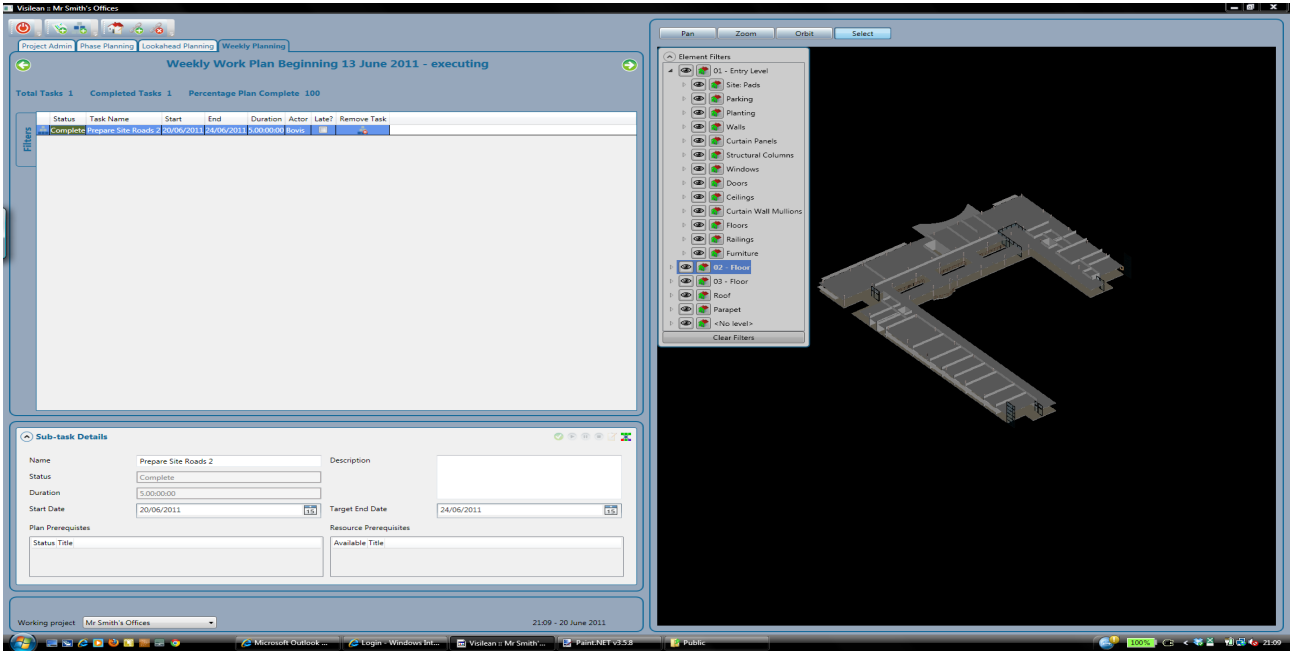


Figure 38. Weekly planning in VisiLean

Table 25. Weekly Planning Specifications in VisiLean.

Requirement	Specifications
Mark the constraint for removal	User should be able to mark the pre-requisite for a task as “Available” using a checkbox. Checkbox should be provided in the Resource Pre-requisite window at the bottom of the screen. On marking the pre-requisite for a task as Available, the task status should change to “Ready” provided there are no other prerequisites for the task.
Mark the task as started	User should be able to mark the task as started. Once started the colour of the corresponding 3d element changes.
Mark task as for attention	User should be able to mark the task as being at risk or for attention. Upon invoking this change, a dialog box should popup and user should be able to describe the nature of the impending problem by selecting a pre-defined category of problem and then supplying additional descriptive textual detail. The corresponding 3D element will change colour to reflect the new status
Mark the task as stopped	For whatever reasons the tasks is stopped, i.e. a resource becomes unavailable etc., the user should be able to stop a task. A dialog box should popup and user should be able to assign a reason from already defined list of reasons and supply additional descriptive text as appropriate. If the task’s previous status was Attention, then some of these details may be copied from those supplied when the initial concern was raised and the Attention status applied. Again, the corresponding 3D element will change colour.
Mark the task as Complete	User should be able to mark a task as complete. An action button should be provided in the model view. Every task will have representation in the model view. It remains the choice of the user whether or not to create the links to enable this display. There should be an action button in model view, which will be used to mark the status of task as “Complete”.
Remove the task from Weekly Plan	1. User should be able to remove the task from the weekly plan. An action button should be provided. On clicking this button, the task will be removed from the weekly plan. The task will be visible in the Look-ahead plan as well as phase plan. 2. If the user wishes to remove a task from the weekly plan, system should give user two options. One option is to postpone the task on selection of which system should ask user to input the new start date. If the user selects this option, all the dependent tasks should get postponed by the same amount of time. Second option is to remove the task from project on selection of which, system should remove the task from the project.
Model Visualisation (BIM)	When a task is selected from the weekly plan, the BIM window should zoom into the corresponding element and highlight the element(s) and also show the status window (showing the status of constraints).

5.5 Developing the System Architecture

The system architecture has to respond efficiently to the functional requirements and specifications set out above. Also, the system architecture has

to provide scalability for additional features to be added in future and also ensure that they are well supported (i.e. from the technological perspective).

The main decision that had to be made was to select the type of application the new system should be, for example,

- A desktop application, which runs on desktop computers (i.e. PC or Mac).
- A web-based system, i.e. a system that runs in a web browser
- A Mobile system, i.e. a system that runs on mobile platforms such as Android, iOS, etc.

There are advantages and disadvantages for each application platform. For example a browser based system provides the most flexibility as it can operate on either a Desktop or Mobile computing device, whereas a Desktop application would provide the users familiar interface and will integrate better with existing desktop applications.

The main deciding factor here was the need for integration with a BIM system, as at the time of development, none of the leading BIM system had a web component that could provide all the functionalities needed. Also, as the VisiLean system needs to integrate with the BIM application to enable linking the production management process with the product model, it needs access to the programming interface, known as the API (Application Programming Interface) of the BIM application platform. The API interfaces of all major BIM systems would only support Desktop applications. Also, viewers available that satisfy the criteria set out in Section 5.6 and which have an API that enables them to be linked to the production management system are only available as Desktop applications. As a result the decision was taken to develop VisiLean as a Desktop application. However, in future when the situation is more favourable for web based development, the VisiLean system could be re-designed for web use.

From a software architecture perspective, VisiLean is designed as a client desktop application that accesses an object based database, running under the Microsoft .NET framework. Initially, for sake of simplicity and rapid application development, the data store was designed to be located on the same computer.

However, it is planned to make the data store component and its interfaces client/server capable in a distributed environment such that it may be possible to have multiple clients accessing the application concurrently. This would further enable different client applications, such as mobile interfaces to the data store, to be provided for different end user groups.

The following outlines the steps taken in developing the system architecture:

- Selecting the technological platforms
- Defining top level concept/system architecture
- Developing the object model
- Developing the database and communication specifications
- Defining the business layer (objects, properties and processes)
- Designing the user interface layer
- Designing reports

5.5.1 Selecting the Technological Platform

One of the initial steps in software development process is selection of technological platform(s) the solution will be based on. It is important to select a platform that will be most suitable in terms of programming features, interoperability, scalability and ease of development. Table 26 shows the selected technologies for development of VisiLean, and the discussion below outlines the factors for their selection.

Table 26. Selecting the technology platform for VisiLean.

Overall Technology Platform	Microsoft .NET (Version 3.5)
OS Platform	Windows
Database	Versant db4o. Transition to a relational database such as MS SQL Server or MySQL later
Development Tools	VS 2010, MS WPF, MS Expression Studio 4.0
Programming Language	C#.Net 4.0
External Systems	Primavera, MS Project or standard PMS (Project Management System) used by construction industry
Reporting	Custom reporting developed within WPF (Windows Presentation Foundation)
Versioning system	Ankh SVN client in Visual Studio, accessing a Subversion server.

5.5.1.1 Overall Technology Platform

Microsoft .Net was selected as the overall technology platform. As the VisiLean system greatly depends on the integration with BIM system(s), the choice of the development platform also depended on the API (Application Programming Interface) availability in the BIM system. As Navisworks was chosen as the BIM platform, and as the Navisworks API was available on the .Net platform, .Net was selected as the overall technology platform.

5.5.1.2 OS Platform

Apart from Graphisoft, which has been available on both Mac and Windows platforms, all major BIM applications are only available as Windows applications (except the new Revit Architecture application which wasn't yet available when the research started). This made Microsoft™ Windows as the main choice of Operation System for development.

5.5.1.3 Database

The database chosen in the first instance was Versant Technologies' db4o (or DB for objects), which as its name suggests is a native Java or .Net object storage medium. The database comes with sophisticated query mechanisms to retrieve objects as required in response to varied criteria. This database was chosen initially over the many relational and document based alternatives primarily as it offers the simplest means to store and retrieve an object graph according to arbitrarily complex criteria with the least effort in development terms. Relational databases, though efficient and undoubtedly more scalable than db4o, require a significant amount of work in terms of so called object-relational-mapping. This is the process of somehow defining a mapping between the two different schemata of object models and entity relations used by object-orientated systems and relational databases respectively.

5.5.1.4 Programming Language

While most of the available BIM applications that expose at least one API do so in C/C++, the chosen BIM platform (Navisworks) also exposes a .Net API which is significantly easier to develop against. Other advantages of the .Net runtime include automated garbage collection, a wide variety of component libraries for

performing various tasks and, in Windows Presentation Foundation (WPF), a rich user interface framework which is natively touch aware and built from the ground up for the Windows operating system, our OS platform of choice. Given that the developer's previous experience included significant amounts of Java development, C# was the chosen .Net language for VisiLean development as it imposed the least overhead in terms of the transition to a new language, it being in many ways very similar to Java. Further it was believed that object orientated (OO) development was the most natural fit for modelling the domain of business objects required for VisiLean's operation, and C# is designed with OO design/development as its primary paradigm.

5.5.1.5 Development Tools

Microsoft's Visual Studio (VS) was chosen as the main development tool for VisiLean as it seemed the most natural, and complete, development environment available for .Net. Initially development was carried out using VS 2008, but was later transitioned to VS 2010 as it was thought that it would be possible then to take advantage of new developments in the .Net 4.0 runtime. As it transpired, there were some versioning issues with Navisworks, which prevented it from exploiting the newer runtime and its features and as such the development reverted to .Net 3.5.

Alongside Visual Studio, the developer used Microsoft Expression Studio, in particular Expression Blend, in designing and building the user interface elements of the application. Once again, this tool from Microsoft was the most complete of its kind for the development of WPF based user interfaces and eased the development cycle thereof considerably by presenting accurately the appearance of the user interface at design time.

Other tools employed in the development lifecycle included Subversion, a source code versioning and management application. Subversion is a client server application designed to let teams manage the evolution and versioning of a code base. During the development of VisiLean, subversion served primarily in its versioning role allowing us to branch development and try out different approaches to solving problems, leaving fallow those branches which proved

inadequate and re-integrating to the main, or trunk, branch those which were deemed suitable for inclusion in the final deliverable.

5.5.1.7 External Systems

For the development of integration code linking VisiLean to other applications, it was required to install and run a number of different pieces of software such as Oracle Primavera P6, Microsoft Project and Microsoft Excel. In attempting to integrate some of these systems, it was required to develop code to leverage their APIs for data import into VisiLean. It is envisaged that in time the data imported would include task data, resource data, external production schedule and shipping data, personnel data etc. At present, only task data is imported however due to the lack of resource to complete more integration code. The primary integration completed so far is that which takes a Primavera exported Excel spreadsheet and automates the Excel application through Microsoft's Office interop (interoperability) assemblies to read the task information therein into VisiLean.

5.5.1.8 Reporting

One of the down sides of the chosen database for VisiLean's first development iterations is that the majority of reporting frameworks expect to be used with a relational data source (as opposed to object oriented). As such steps have been taken for building reports into VisiLean using the components available in WPF itself. This will relieve VisiLean of any dependency on a third party library for this important area of functionality. An open source project called the WPF Toolkit is available which comes with some basic chart controls that have been employed in VisiLean's reporting features.

5.5.2 Defining Top Level System Architecture

During the initial stages of software conceptualisation, the academic literature in the domain of lean construction management was reviewed, particularly the Last Planner System™ (Ballard, 2000). From these readings a conceptual domain model for lean construction management was developed, which helped identify the primary functional areas that would be required of a software system to support the process. Once these areas were identified, initial design of the

supporting functions of a typical software system was carried out, such as data storage, communications and user interface requirements. There are elements of the process model that map into parts of these support functions, and which begin to determine the shape of the final software in terms of its architecture and operation. For example, the user interface must embody the process of lean construction management, which is embedded into business logic in the application, whilst simultaneously remaining decoupled from the logic and process to the greatest possible degree in technical terms. This is to maintain the boundaries of functional components within the system and to aid in making various parts of the application usable in more than one context, such as native mobile applications accessing the business logic interfaces without requiring reference to the desktop UI components for the whole to function correctly.

The architecture that was finally adopted incorporated a multi-tier approach having the database with a data access interface at its bottom level, followed by business logic modules accessed through service interfaces by a UI tier at the top level as shown in Figure 39. Also feeding into this architecture are external systems, for which separate modules exist to manage the communication. For example the import of scheduling data from Oracle's Primavera is handled this way. Further, as the core of the system does not handle the geometric data of BIM models, another external system in the shape of Autodesk's Navisworks was selected to manage that aspect. This is integrated at the UI level for end users to interact with. Again there is a dedicated module to handle interaction with this system through interface definitions of the operations that are to be realised on the BIM model itself.

Another, as yet unimplemented, part of the system is the interface to other business systems such as component manufacturer's production management systems. These modules would be designed to bring in data about production and delivery schedules for the materials and components required to execute the tasks in the project plan, such as delivery date etc. From an architectural standpoint, they would be plug-in modules that could be deployed into the application as and when required to interact with other systems. It is envisaged

that this interaction would take place over Web Services protocols such as SOAP or REST (Representational State Transfer)-based services.

It is further envisaged that the VisiLean application will eventually be a distributed application in nature and cater for multiple simultaneous users. This distribution of application components is reflected in the future architecture diagram (Figure 39), wherein the application layers defined above are separated onto different physical machines for scalability and accessibility. A higher resolution version of Figure 39 is provided in Appendix C.

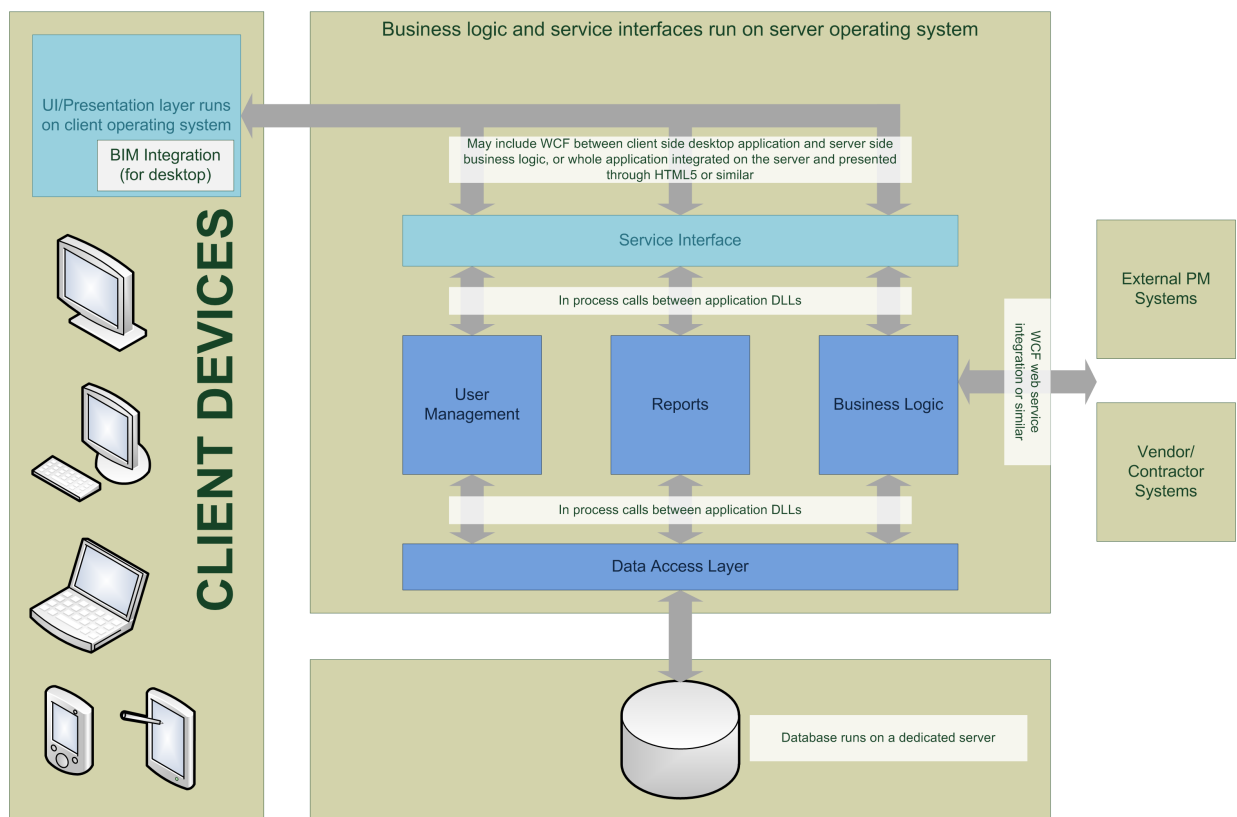


Figure 39. Top Level System Architecture for VisiLean.

5.5.2.1 Designing Main Application Modules

The main application modules within the VisiLean application were identified next by further decomposing and describing the domain model and primary functional modules. The modules below were identified and implemented as Visual Studio projects in the C# language. Having each module implemented as separate project aids in the effort to maintain code libraries that are decoupled from each other and which could reasonably be reused in a different version of

the system independent of some of the other modules. Each project compiles to its own Dynamic Link Library (DLL), which is an application sub-part loaded into the main application as required at run-time. The only Visual Studio project that does not emit a DLL is LastPlannerGUI, which compiles to an executable (EXE), with which many end users will be familiar from their use of other computer applications for other tasks. The following describes the Visual Studio projects that comprise VisiLean.

- **LastPlannerLib** – This is the core module of VisiLean having the business objects and logic, the data access interface definition and the ‘services’ (business methods) used to manipulate the business objects.
- **VisiLeanBimLink** – This is a set of interface definitions that describe the means by which BIM objects are referenced from VisiLean and BIM applications are controlled in terms of showing/hiding elements, views etc. This module was created as initially the thought was to maintain a BIM application agnostic stance whereby any BIM application having an accessible API could be potentially linked to VisiLean. The decision to use Navisworks as the first demonstrator was made as it offers an embeddable control that would appear to be part of VisiLean. Other BIM applications would essentially need to be automated in a ‘side-by-side’ configuration where the BIM model is presented in its own application window. This module also contains the interface definition for a data access component that stores and retrieves data about the links between the main VisiLean application and BIM models. Thus the databases for the main application and links to BIM models are in fact separate entities.
- **LastPlannerDb** – This is an implementation of the two data access interfaces mentioned above, for the db4o database. There is also a part implemented version for relational databases accessed through the NHibernate framework, though this is incomplete and is not being actively developed at present.
- **VisiLeanExcelAutomation** – This module implements the import of Primavera V6.0 data via Microsoft Excel into VisiLean. This is a two stage

process whereby the data must be exported from Primavera into an MS Excel file, which is then parsed and the data imported into VisiLean. Currently this is a one-way process with no updates being sent back to Primavera.

- **NavisworksWPFControl** – This is an implementation of a WPF UserControl, which embeds the Navisworks .NET Winforms control and implements the interfaces defined in the VisileanBimLink module to provide BIM model display and manipulation to VisiLean.
- **TreeListView** – This is an extension of the WPF TreeView control, which combines the tree view and list view to provide an expandable hierarchical grid, which is employed in the UI in the Phase Planning tab.
- **LastPlannerGUI** – This is the module, which implements the VisiLean UI in WPF and forms the main executable for the application. As such it has dependencies on all the other modules mentioned above. It also manages the creation and display of BIM popup windows for the embedded BIM model configuration (Where the BIM model is presented in ‘side-by-side’ configuration, the popups are generated by the BIM application itself and managed through the VisileanBimLink interfaces).

5.5.2.1 The object model

Finally, having identified the major functional components of the VisiLean system, and their representation as software modules, the design of the actual object model for the system was initiated. This entailed the further breaking down of the descriptions for the modules to determine precisely by noun-verb analysis, the required objects and the interactions between them. In the first instance this mainly involved the design of the business logic classes such as Project, Phase, Task, Sub-Task and Resource and the service interfaces through which they would be manipulated. As the names of the classes noted above may suggest, the object model initially had only three levels of hierarchy for project activities, Phase, Task and Sub-Task. These three classes were later superseded by the Activity class, which could be arbitrarily nested to any level of hierarchical depth. The primary class to represent project resources is the IResource interface, which has a number of concrete implementations including Material,

Component, Actor, Space, Plan and Information. All of these resources can be further categorised by the assignment of a Category to the resource. Again, in the initial object model, there was only one category assignment per resource, but this changed over time such that it is now possible to categorise a resource under several different categories. The ICategory interface is the basis of the categorisation sub-system and like IResource has a number of sub-classes associated with particular types of resource. For example, the Actor class will have a Role associated with it, the Role being a specialisation of the ICategory interface for Actor instances. The MaterialCategory class features a number of properties common to consumable resources such as materials and components, and indeed is applied to resources of type Material and Component. These, along with classes representing both Look-ahead and Weekly plans form the primary business process logic classes of the VisiLean system. Other classes, though numerous, play a supporting role in the system such as defining UI behaviour or accessing the database to retrieve objects. Figure 40 below shows a section of one of the class diagrams developed for the VisiLean system. On it can be seen some of the classes mentioned above along with a number of implementation specific classes such as PlanBase and TaskBase. These implementation specific classes exist to collect common functionality into a single place thereby reducing duplication and making the propagation of updates across all affected classes a matter of edits to one file rather than four or five. This centralising of common functionality is known as inheritance and is one of the major tenets of the object orientated software design paradigm that was followed in the development of VisiLean.

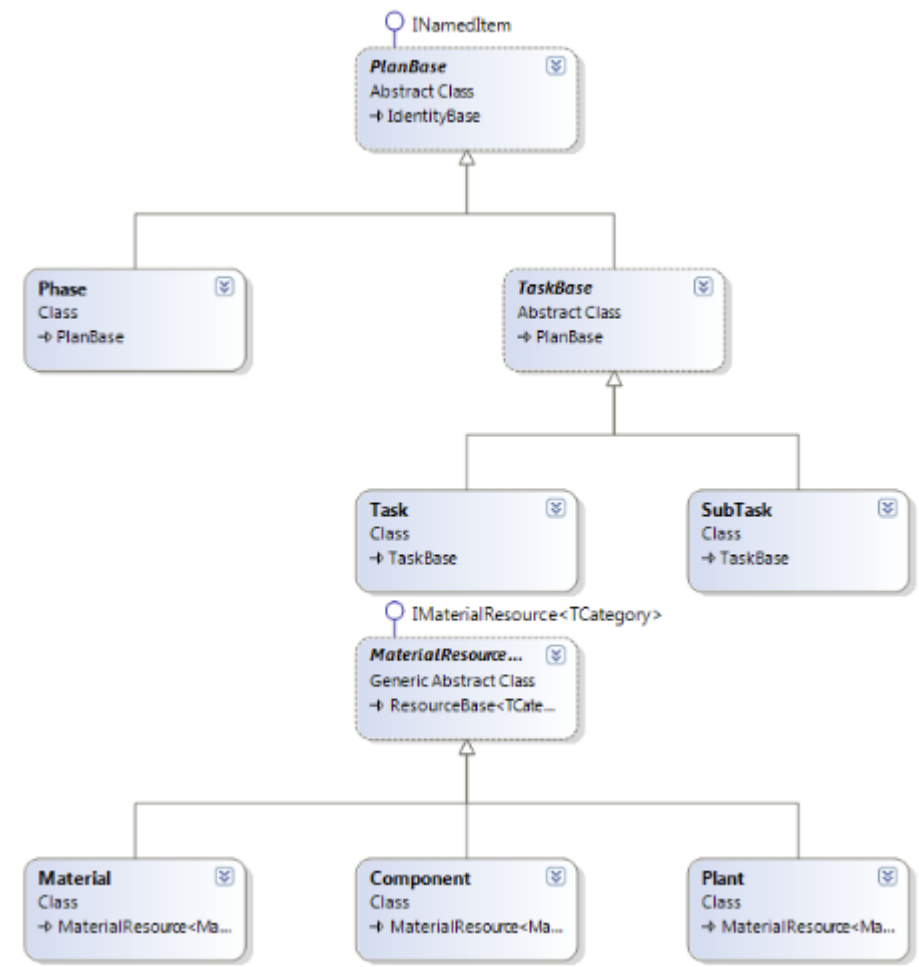


Figure 40. Example of VisiLean Object Model.

5.6 The iterations of VisiLean

This section describes the development process for VisiLean in three major iterations. As such, the Scrum method of development was followed, and as a result VisiLean went through daily iterations. However, for sake of clarity, the development has been conceptualised in three major iterations. The overall range of features available in VisiLean are listed in the functional requirements document, here the discussion is regarding the process of development and the reasons why these features were implemented in the particular sequence. Each section describes the features of VisiLean accompanied by screenshots of the prototype. Due to relatively limited space available in the thesis page layout, high resolution images are provided in Appendix C. Table 27 below shows the main evaluation goals of each iteration.

Table 27. Main VisiLean Iterations.

Iteration	Duration	Main Evaluations
1	2 months	Basic interface evaluation, Top level process, Top level model functionality
2	6 months	Refining interface features, resource management evaluation, deciding task hierarchies, detailed process evaluation
3	10 months	Main user interface, detailed user interface (buttons, layout, item selection), communication, resource management, constraints management, Model interaction

5.6.1 Iteration 1

The main goals of the very first iteration were to validate the main user interface design, and then decide the top level planning process and model functionality. This was a very quick iteration as it did not focus in detail on feature selection of either the planning or model integration processes, but on validation of the top-level goals of the process.

5.6.1.1 User Interface

The main decision regarding User Interface at this stage was about placement of planning and model window, overall button layout, interface layout and the general look and feel of the interface.

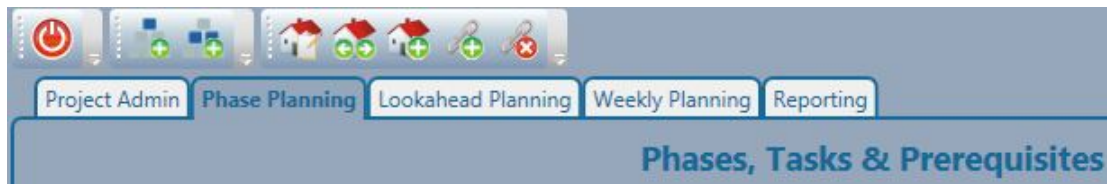


Figure 41. Tabbed User Interface in VisiLean.

The first shell of the application had a rigid frame between the planning and model window that didn't allow resizing the model or planning window if there was a need to do so. After evaluation, a decision was taken to make the frames flexible so either window could be resized to adjust to the model view to enable proper visualisation.

It was also decided to have a tabbed interface that allowed quick switching between each planning functions, which is shown in Figure 41. Also, it was decided that constraints analysis would be carried out using checkboxes, i.e. each

constraint will have a checkbox next to it, clicking it would make that particular constraint available in the system.

5.6.1.2 Planning Process

At this stage, the actual planning process had not been implemented, however, decisions regarding the top-level workflow were taken which led to its implementation in the second iteration.

In the first iteration, the planning process would support a three level activity hierarchy structure, namely phase, task and sub-tasks. It would be possible to have finish-start relationship between these activities. It was decided that each activity (i.e. phase, task or sub-task) would have an actor assigned to it. The actor could be an organisation, a team or an individual. This actor will also be responsible to manage the constraints within the planning process, and also to manage the task during execution.

5.6.1.3 Product Navigation (BIM window)

The main decision regarding the model integration was regarding the selection BIM application, which would satisfy the functional requirements and also have an API (Application Programming Interface), which would let the model be integrated with the VisiLean application. Once Autodesk Navisworks™ was selected as the main platform, the decision regarding the navigational functionality was made, and Panning, Selecting, Zooming and Rotating were chosen as the main navigation functions.

5.6.2 Iteration 2

A range of feedback capturing methods were used between iteration 1 and iteration 2 and also during the development of 2nd iteration, which contributed to the development of features selected in 2nd iteration. The second iteration was the most intense part of the functional development where most features of VisiLean were defined and implemented.

5.6.2.1 Refining the interface

The first iteration had simple buttons, which were small and made it hard to identify what their purpose was. In the second iteration, new graphical buttons

were introduced which provided visual feedback to the user and made the selection more intuitive.

The main process-product integration and visualisation was implemented during this iteration. Here, a process status symbol was designed that would be overlaid on top of the connected BIM element when a respective task was selected in the planning window. This graphical status symbol would have the following information:

- Name of the task
- Person/team/organisation responsible
- Constraints and their status
- Priority

Overall, the colour of the status box would match the status colour of the task according to the colour coding explained in 5.3.1.1.

5.6.2.2 Task hierarchy

One of the core functions of the VisiLean application is planning and hence designing the task management functions in an effective way was very important. Following several demonstrations to focus user groups during and after 1st iteration, feedback from potential users regarding task hierarchy was that the application should not restrict the users to a three level activity hierarchy. As the planning process starts to get detailed, especially during look-ahead and weekly planning sessions, there may be instances where the tasks have to be decomposed into deeper levels. Hence, it was decided that the users would be able to break an activity down to their desired level and will not be restricted to a three level hierarchical structure. However, it should be noted here that this would also have to be matched in the BIM model elements, and the model should be detailed enough to support the level of detail the tasks are being planned at.

A number of decisions regarding task sequencing and decision making process if a task gets delayed were also taken during the 2nd iteration. The key decision in this respect was regarding the sequencing and changes in the dates/duration of connected tasks and the overall project (if the changes are deep) if a task gets

delayed. It was debated whether to automatically update the dates of subsequent tasks and the parent phase (or task) if a task or subtask gets delayed or rescheduled, or should the decision be left to the user and provide the information to the user about this potential delay. It was decided that it is best to leave the decision to the user whether he/she wants to keep the parent phase or task dates unchanged and will mitigate the situation through resource management or whether the system should calculate the delay and appropriately change the parent phase/task dates and if needed cascade the change (if the parent phase/task is connected with other phase/tasks and subsequently the project end date). This particular issue also directed the focus towards another aspect related to the critical path of the project, i.e. if a phase or task falls within the critical path of the project and has a potential to affect the duration of the project. Hence, a new feature was implemented called “show dependents”, which will be made available to each task. Upon pressing this button, the system will graphically display all the connected tasks/phases with the selected tasks (i.e. the position of the selected task with respect to the critical path of the project).

5.6.2.3 Organisational hierarchy

In the first iteration, the organisational hierarchy was only down to two levels, Organisations and Individuals (which belong to that organisation). In VisiLean each task is assigned to an actor (i.e. the entity responsible for executing the task). During the discussions with user, it emerged, that as many tasks are performed by a pre-defined group of individuals, i.e. teams, provision to group such individuals should also be provided in the VisiLean system. Hence, in the second iteration of the software, an additional entity was added to the organisational hierarchy.

5.6.2.4 Resource management

Resource management and constraints analysis and management are two most important aspects in production management, hence in VisiLean. These two aspects are related to flow or “F” view of production and help keep the production running efficiently and reduce variability. In the first iteration of VisiLean, there was “one to one” mapping between a task and a resource, where each individual resource had to be created separately within the system. Also, in

the first iteration, the VisiLean system did not distinguish between the consumable (for example cement, steel, paint etc.) and non-consumable resources (i.e. equipment, manpower, space etc.). This short-coming was identified during the discussions and feedback while demonstrating the 1st iteration of the software. In the 2nd iteration of the software it was made it possible to distinguish between consumable and non-consumable resources and also the notion of total quantity available for any given resource was introduced. For example, there could be 500 bags of a particular grade of cement available (delivered) on site out of which 475 could be allocated between three tasks (the system would calculate this total automatically) and inform the user that 25 bags remain. If the user tries to allocate 100 bags to a task in the look-ahead plan, the VisiLean system will allow the user to release this constraint before 25 additional bags would be delivered to the site.

5.6.3 Iteration 3

The 3rd iteration was mainly about refinement and fine-tuning of features based on the pilot implementation and feedback received following the 2nd iteration. However, due to limitation of resources and time, a number of features requested by users could not be implemented in the prototype. Additionally a range of features, which were planned for development during the initial functional requirements development and development of system architecture could not be implemented. These features are listed in 5.7 and 5.8 respectively. These features could also be taken as the direction for future research and are further discussed in Chapter 7.

5.6.3.1 Interface Improvements

In the modelling window, from two main improvements were made regarding the navigation options. Options to “walk” and “fly” around the model were added following requests from users. These two functions make navigating large models and getting a snapshot view of the project much simpler.

Through the user feedback, requirement for more graphical information in the task status window box that was overlaid on the BIM element emerged. Previously, in the second iteration, this box only included the task name and the

responsible actor (organisation, individual or the team performing the task). As new requirements emerged during evaluations, the task status window in the third iteration included a traffic light type of symbol showing the current status of the task along with a list of constraints. A checkbox was also provided next to the constraint making it possible to release constraints directly from this box.

Additionally, a visual symbol on the planning (task) window and its corresponding BIM status window was added showing resource clashes (i.e. if a non-consumable resource such as a crane or a work team has been booked by multiple tasks at the same time). This symbol will help identify such clashes effectively so that they can be dealt with prior to the tasks being released to the weekly plan.

5.6.3.2 The Planning Process

Two workflow related changes were made to the planning process. In the earlier iterations, both the look-ahead and weekly planning process involved the user having to select the tasks from a list manually, which were then added to the respective plan. The feedback from the users was that this added an unnecessary action, and once the look-ahead and weekly planning windows were defined the tasks should be automatically added to that plan. If a certain task cannot be “made ready” the system should provide an option to remove it. Hence, this minor change was applied.

The other major change request received from users was regarding the auditing (or change tracking) capability of the system. The previous iterations of the VisiLean system deployed logging capability, however the logging was mainly to track system errors and not changes made to tasks, which was not made available to end users. However, the users highlighted that this is one of the major pitfalls of the current manual processes, that the decisions taken during planning sessions and also during execution are not logged and hence cannot be tracked back when needed in future. Such track changes facility would enable the analysis in case something went wrong, or simply to add to the knowledge of the team during the later stages of the project. Hence a facility was added, where the VisiLean system would keep track of all the changes made to tasks, and users

can add reasons when major scheduling changes are made to the tasks. A report is then provided which would make available the audit trail linked to any particular task or phase.

5.6.3.3 Resource Management

A visual icon was displayed on the task window and also in the BIM window (in the task status window) to indicate if there was a conflict due to a resource being booked to multiple tasks at the same time. This visual icon will indicate which tasks are clashing and prompt the user to take action.

5.6.3.4 Reporting

None of the previous iterations of the software implemented any reporting features. Following the discussions with the potential users, it was decided to develop a reporting feature that would include the following reports.

- **PPC** – one of the most important measure in the lean planning process is the “percentage plan complete”, which shows the percentage of tasks complete in any given week and plots it on a graph with time represented on the horizontal axis. In VisiLean a PPC chart will be automatically provided based on the performance of weekly execution plans. In VisiLean it is also possible to output a PPC chart for any given duration or for a sub-contractor.
- **Reason for non-completion** – When a task can’t be executed from the weekly plan, the foreman (or the task leader) has to provide a reason why the task wasn’t performed within the given timeframe. The reason for non-completion tracks these reasons over a project duration and are represented through a pie chart in VisiLean. Similar to PPC, it is possible to output this report for a given duration or a by a subcontractor.
- **A3 Weekly report** – The weekly report is a combination of PPC, Reasons for non-completion and a list of next week’s tasks and the status of their constraints.

5.6.3.5 Communication

Similar to reporting, communication was also a new feature in the 3rd iteration, and also very important. A number of communication requirements emerged

during the demonstrations of the 1st and 2nd iterations, where one of the most requested requirement was that to notify the actor (team/individual) performing the next task when the predecessor is completed (however, the execution of the next task could only start if it is free of constraints). Similarly, the system will send a message to the actor performing the particular task and the next one in line if it is getting close to the deadline or delayed. If the task is getting significantly delayed (a period set by the project manager), the system will notify the site manager and the project manager. A host of other communication tasks were included in the 3rd iteration.

Ideally, it was intended that the system will have a notification centre of its own, and when a user logs in to the system he/she would receive the messages stored in the inbox. And certain messages related to task execution will also be sent via text messaging or mobile application notifications. However, as the VisiLean system does not yet implement a distributed access facility where individual users can login and access to the system is controlled, such a feature cannot be implemented. Hence, it was decided that all the communication in the 3rd iteration will be carried out using emails. The system would generate and send an email to the intended recipient(s) when any of the triggers set by the system is activated.

5.7 Summary and Analysis of Feedback

This section summarises the feedback received during the demonstrations of the VisiLean prototype as part of the evaluation process. A tabular summary of the feedback is presented in Table 28.

As interviews and workshops fall within qualitative research, guiding principles from the qualitative research domain were applied when selecting interviewees, operating procedure and sample size. The discussion regarding sample size and saturation has been provided in Chapter 2. With the feedback collection exercised (through interviews and workshops) it was found that a sample size of 5 was sufficient, as saturation seemed to be occurring at that point. As the experts belonged to the same industry and had somewhat similar roles in their organisation (both in workshops and interviews), the theory of consensus was

also confirmed. There was a significant repetition and similarity of opinion in the responses from interviewees and workshop attendees. However, it must be acknowledged here that majority of the respondents were construction professionals from large industrial organisations and it is possible that the opinions could have been different if the range of professions of respondents had been wider.

Also, selection of organisations and persons to be interviewed is one of the most important criteria when carrying out qualitative studies. Nature of the organization, size, familiarity with the subject area and geographic location are important criteria for selection. As the study falls within the realm of production management in construction, and specifically deals with lean construction and Building Information Modelling, it was important to select participants who would be familiar with the subject area and have previous experience in either implementing it or at least have knowledge about the subjects. From this perspective, interviewees and workshop participants were selected from large contracting organisations, which had prior experience of Lean and BIM implementation, and were based in the UK (with the exception of two Finnish organisations). As design has not been considered to be within the scope of this research, interviewees from this (design) background were not selected for feedback collection.

Table 28. Summary of feedback received during evaluation.

Aspect evaluated	Feedback and its Analysis
Relevance of research	All respondents agreed that the research is quite relevant and timely. Almost all respondents (all except #4) mentioned that they are currently implementing both Lean and BIM. However, most organisations expressed a concern that there are no computer-based systems that help with the site based implementation of the Last Planner system (or that they have been custom solutions such as using Excel Spread sheets) causing much manual processing. The representatives of two companies mentioned that they are trying to use both Lean and BIM simultaneously but are facing issues due to a lack of an integrated system. One of the respondents also mentioned that a public sector client has been pushing lean across all projects and there is an internal desire to implement lean, which makes the concept very timely.
Usefulness (practicality)	Most respondents answered this question as part of answers to other questions. Two respondents mentioned that their current Last Planner™ workflow of using Post-It™ notes and Excel spreadsheets does not keep an

Aspect evaluated	Feedback and its Analysis
	<p>audit trail of decisions, and hence it would be useful to have a system that supports a systematic way to support the Last Planner™ system.</p> <p>However, most respondents expressed concern that in the past, many solutions they had tried to implement on site had failed due to the rough working conditions, lack of communication channels, unskilled nature of workforce and high complexity (steep learning curve) of the system being implemented. Hence, they expressed a desire that any solution being implemented should be very simple and intuitive to use with minimal training needed (as worker turnover remains high).</p>
<p>Should the research be advanced to further stages (asked at the early stage of research)</p>	<p>As a part of the design science/constructive research approach, this question was asked during early demonstrations/discussions about the solutions to identify whether the solution is worthwhile and feasible to carry forward. All participants unanimously agreed that the solution and the concept are relevant and should be developed further.</p> <p>One of the respondents mentioned that in the past such research has failed to make an impact in the industry, i.e. the commercial (software) solution providers continue to provide features supporting CPM based planning and scheduling systems and ICT solutions that do not tackle site based processes or lean workflow efficiently. According to the interviewee, it would be wise to collaborate with a commercial provider so that they would incorporate lean production management and product and process integration, visualisation and synchronisation features in their upcoming software revisions.</p>
<p>Key important features</p>	<p>All respondents agreed that</p> <ol style="list-style-type: none"> 1. support of collaborative planning workflow, and 2. integration with BIM (to support visualisation of production planning) <p>are the two most important features. Others added that having an integrated system would save the considerable effort of maintaining separate database systems and would improve the quality of planning and control functions.</p>
<p>Key modifications needed and missing features</p>	<p>Three out of five respondents mentioned that such issues (of needed modifications and missing features) only emerge once the system is pilot tested. However, at least two out of five respondents (and some participants at subsequent workshops) mentioned that adding quantity and cost information to tasks and having an integrated cost/value reconciliation system would be a big advantage.</p> <p>Also, an interviewee who had been using location based scheduling for preparing master plans added that the possibility of adding a location (i.e. dividing the site/project in various locations, either by floor or by zones) to the tasks would be a crucial feature for their company.</p>
<p>Implementation test and readiness for a pilot</p>	<p>All respondents agreed that if such a system were available, they would like to implement it on their projects. This question was asked in terms of Kasanen's (1993) weak market test, i.e. whether a manager agrees to implement the system in their organisation. Also, all respondents agreed to carry out a pilot project if a suitable project and resources were found.</p>
<p>General comments</p>	<p>The UK based contractors pointed out demands by the clients as the biggest drivers for lean and BIM implementation. It was also mentioned that having strict access control to manage "who can see what" in the system would be quite important, as such a system cannot be implemented in isolation.</p>

The feedback was received after the first year of research, when an initial prototype (proof of concept) of the VisiLean solution was presented. The individuals interviewed belonged to large construction organisations (2500 or more employees). All respondents were familiar with Lean Construction process and were implementing BIM in either one or more of their projects. This proximity/familiarity with lean and BIM was one of the main criteria for selection of participants in both interviews and workshops.

The first set of interviews gave an early insight into the requirements and whether the research solution was relevant to the industry (it is one of the primary requirements of the constructive research/design science approach). The feedback received was taken into consideration when designing the VisiLean prototype further.

5.8 Unimplemented features

As reported earlier, due to time and resource constraints not all features identified as missing through discussions or which participants requested during demonstrations and pilot implementation could be implemented in the three iterations outlined above. This list is slightly different from “plan for future development” list below in section 5.9 as the features listed in this section were already identified in the beginning of the project and were known to the research team as being out of scope for current development. However, for future development, both sets of features, as listed in Section 5.8 and Section 5.9 are important.

5.8.1 Cost and quantity integration within the task management

Two of the most requested features during the demonstrations were the inclusion of cost and quantity data from the BIM model and also from the Tendering and Estimating database. It is now possible to extract quantity data from BIM models if the models are accurately developed and detailed. Similarly it is possible to link the cost database either directly within the BIM software or through external cost management systems. Also, if models were not used during the tendering and estimation phase, another set of quantity and cost information could be available (which could also include resource information, i.e. amount of

resources allocated to each work package). During demonstrations and discussions it was identified that access to this information would help during planning and execution and also would also make it possible to carry out comparative analysis between the planned and actual consumption of resources. In future, if the facility to capture cost data during execution, it could be possible to generate reports such as “Cost Value Reconciliation” directly from the VisiLean system.

5.8.2 Quality and safety management workflow

In lean, quality is part of the production planning and control and is not a separate function as such. Each worker in the production system is responsible for managing quality and ensuring that each product meets the standards. However, in practice this has not yet been realised in construction and also from contractual perspective there may be requirements that have to be met to demonstrate a task meets the quality requirements. During the pilot project implementation of VisiLean, and also during other demonstrations, users requested a quality and safety management workflow feature.

From quality management perspective, the users requested that following the completion of each task, the task supervisor (or the internal quality assurance authority) should be notified so that he/she can carry out the inspection and mark the task as complete. Following this internal inspection, if needed the external authority (mostly client or a client representative) should be notified to carry out the final inspection and marking the task as complete to the satisfactory standard. It was requested that these actions should also be recorded and the system should provide a facility for the user(s) to attach photographs or other media files to tasks in VisiLean.

Similar to quality, safety is also an integral part of the lean production management system. Due to the highly visual nature of the VisiLean system and much detailed planning capabilities, several users pointed out the opportunity to carry out safety analysis of planned work during the collaborative planning sessions. In VisiLean it is anticipated that the worker in charge of safety (safety manager) should be given access to the system, so that he/she can approve the

weekly plan (preferably during the weekly meetings) in the system and authorise the work to start. This could also be treated similar to the constraints management and the tasks could only be released to workers once the safety manager has approved the plan.

5.8.3 Multiple task visualisations in the model window

Currently there is a one-to-one mapping between a task in the planning window and the task status window in the (BIM) model. However, feedback received from participants indicated that it would be valuable to select multiple tasks in the planning window, where their respective status is displayed in the model window through the task status window and also through colour coding. For example, selecting a phase in the planning window would select and highlight all BIM elements in the model window, which are linked to the tasks that are planned under that phase. This way it would be possible to visually check the status tasks in a quick and efficient way.

5.8.4 BIM based task creation

Currently there are two ways to create a task(s) in VisiLean, either by importing it from other planning software or by creating it directly in the planning application. However, during demonstrations a request for a new method of creating tasks was received; whereby selecting a model element in the BIM window and clicking a button would automatically create a task with pre-defined information from the BIM model. Here, information such as the element name, hierarchy in the project, quantity and cost data (if present) and other geometrical data would be used to populate certain fields. The new task will be created under a phase, which is selected before clicking the “create task” button. The main benefit of providing this option to the users it to make the system as user friendly and intuitive as possible, as this method of task creation is not only highly visual, but also has a potential to save time by populating the task information extracted from the model.

5.8.5 Resource Booking Management

Following the changes made to resource management in iteration 2, where the distinction between consumable and non-consumable resources was made, in

the third iteration, a booking management system was added which would let the users allocate a certain resource to a task for a pre-defined period. During the demonstrations of the second iteration, the users highlighted a particular need to book high-demand resources such as cranes and specialised equipment or spaces, which will enable a much tighter control of such resources and minimise clashes with other tasks. As a result, a feature to book time-slots for individual non-consumable resources was implemented.

5.9 Plans for Future Development

As mentioned above, there was a set of features, which although were planned from the outset and were part of the initial functional specifications, could not be implemented in the three iterations of VisiLean due to time and resource constraints. However, VisiLean research is ongoing, and it is hoped that these features along with the unimplemented features described in Section 5.8 should be prioritised for in future iterations. These features are outlined in the following.

5.9.1 Mobile Interfaces

From the outset, development of mobile interfaces was recognised as one of the core features of VisiLean. As construction is a field-based activity the use of physically constrained technological equipment (such as a desktop PCs), to access a production management system such as VisiLean may not be appropriate, and also as the use of laptop computers in the field could prove to be cumbersome. On the other hand mobile technologies such as Tablet computers and smart phones are becoming highly sophisticated and powerful, increasingly being used on construction site. Most BIM software vendors, including AutoDesk, Bentley, Tekla, and Graphisoft now have applications on mobile platforms that help visualise the model in the field.

VisiLean being a production management application, a significant amount of information could be used to support execution activities in the field. The following activities will benefit from development of mobile interfaces:

- Accessing planned tasks (for a given team or individual), and their current status

- Starting, stopping and completing tasks by simply clicking a button
- Taking pictures and videos of and linking them to tasks (for example, of completed tasks, innovative ideas or problems).
- Accessing task and model related information when needed

None of the current BIM viewers on the mobile platforms provide access through API (Application Programming Interface) and hence it is not possible to link VisiLean to them, however once the viewers with API are made available, model integration on the mobile interface will be considered.

5.9.2 Knowledge Management

Knowledge Management in production management involves sharing tacit and explicit knowledge with co-workers and is a core part of the continuous improvement cycle in lean construction. There are a number of platforms or solutions for sharing explicit information, such as Project Extranets, Emails, and other project information management systems. BIM can also be viewed as one such platform, which enables sharing explicit product information. However, capturing tacit knowledge is more difficult and there is a general absence of systems, which help with collaborative sharing of tacit knowledge. With the advancement of Social Networking applications such as forums, blogs, wikis and other platforms such as Twitter, can be used for collaborative knowledge sharing. These applications are successful in sharing tacit knowledge especially due to their informal and social nature, which nurtures and supports sharing of knowledge within communities (Dave and Koskela, 2009).

In VisiLean, a task centric knowledge management solution is anticipated, which will let users discuss any issues related to a particular task. There will also be an open space for discussion related to general issues (and not to a particular task). A combination of social media tools such as an online forum and twitter will be used that provide a user experience that is almost real-time and personal. Through such an integrated platform, the users will be able to discuss ideas, take them through a cycle of refinement through discussion and develop solutions, which are then documented and shared across a wider community.

5.9.3 Simulation of a look-ahead or weekly plan

Currently in VisiLean (iteration 3), it is not possible to simulate either the look-ahead or weekly plan. During discussions with potential users, and demonstrations the requests for simulating these plans were received. Users saw the potential and benefit in visualising the sequence of selected tasks to identify any sequencing issues and also to understand the execution plan in a more detail. As currently the VisiLean application uses Navisworks, which incorporates a 4D simulation engine (which is accessible through API), it would be possible to simulate a selection of tasks in 4D.

5.10 Summary

In this Chapter, the process followed while designing and developing the production management solution in response to the problem outlined in Chapter 3 and opportunities identified in Chapter 4 was described. The main goal of this solution, i.e. to provide computer system support to the production management processes was achieved by carefully identifying the core production management requirements and then requirements from previous research. Based on this and also through discussions with participants, a framework of requirements for a production management system was developed. This framework was then developed into three main categories, i.e. functional requirements, technology requirements and user interface requirements.

After careful consideration, Scrum from the Agile Development methodology was selected and followed throughout the project. As Scrum is a highly iterative and incremental process, there were short loops of design, development and evaluation. However, for sake of simplicity, the development was categorised in three main iterations, which have been described in Section 5.6. While designing VisiLean features and going through the development iteration cycle, experience and knowledge of external research participants were very useful and contributed to the robustness of the solution. The constant feedback received from the research participants through workshops, demonstrations and meetings was taken into consideration while designing and developing VisiLean, and it was an incremental process, however, for the sake of clarity the evaluation process will be discussed in Chapter 6.

Selecting the technology platform and developing the system architecture were complex and time-consuming processes, due to a large number of options to be evaluated. In the current solution, Autodesk Navisworks has been chosen as the BIM technology platform, however the architecture has been designed in such a way (by keeping the business logic of process and product visualisation independent) that in future any BIM solution that satisfies the criteria can be selected, as long as it can be accessed through an API. This aspect will enable the potential users select whichever technology platform they are familiar with, and also enable development of multiple solutions with a range of technological platforms.

For future research, one of the most significant change will be move towards a web enabled system, either through a complete move to a web based solution, or a combination of desktop and web based applications which allow distributed access to the system, and granular access control. The main constraint in developing a complete web based system is the current unavailability of a capable BIM platform that has a web interface (for at least model visualisation) and which offers a capable API. This however is changing fast as a number of new solutions are coming to market. Also, by using a programming language such as HTML 5, the application can be browser based, but can also be accessed through mobile devices. Hence, it could truly function as a Universal application, which is accessible from all platforms (including Mac, PC, Linux, Android and iOS).

The other significant change that is anticipated in future releases is how the application synchronises or integrates flow information (regarding constraints). Currently the project administration information has to be input manually, however, going forward, use of web-services to dynamically link to relevant information systems (such as procurement, asset database, estimating, etc.) will reduce the requirement of manual input and increase the accuracy and speed of information availability.

Section 5.6 describe the current features of VisiLean and their development process while section 5.7 provides a summary of the feedback received during

evaluations and their analysis. Subsequently, Sections 5.8 and 5.9, outline the features that could not be implemented in the current version.

It should be noted that as VisiLean has been developed as a research system with limited resources, and mainly as a proof of concept of a Lean and BIM system, it lacks the sophistication of a commercially available system and has many limitations.

Overall, the design and development of VisiLean has been through an iterative and incremental process, where constant feedback from the industry helped refine many of its features. VisiLean is still a prototype system with many limitations, and future research and development can potentially make it a capable production management system that will help integrate, synchronise and visualise information for efficient production management on a construction project.

6 Evaluation of VisiLean

6.1 Introduction and selection of evaluation methods

Evaluation as a part of design science method was presented in Chapter 2. Here a detailed explanation of the evaluation methodologies and the appropriate process followed for VisiLean evaluation is provided.

All major authors on design science emphasise the need for a definition of appropriate metrics to evaluate the design artefact (Hevner et al., 2004; March and Smith, 1995; Lukka 2003). Hevner et al. (2004) provide factors against which IT artefacts can be evaluated:

- Functionality
- Completeness
- Consistency
- Accuracy
- Performance
- Reliability
- Usability
- Fit with the organisation and others

As discussed in the previous section, design and development of an information system is an incremental process. As a result the evaluation phase provides essential feedback to the construction phase regarding the quality of the design process and the artefact that is being developed.

Hevner et al. (2004) mention that the evaluation of the artefacts typically uses methodologies available in the knowledge base. They provide a summary of these methods, which is provided in Table 29. It is well established that the efficacy and goodness of an artefact can be rigorously demonstrated by well-selected evaluation methods (Basili 1996).

Table 29. Design Evaluation Methods (Hevner et al., 2004).

1. Observational	Case study – Study artefact in depth in business environment
	Field Study – Monitor use of artefact in multiple projects
2. Analytical	Static analysis – Examine structure of artefact for static qualities (e.g. complexity)
	Architecture Analysis – Study fit of artefact into technical IS (Information Science) architecture
	Optimisation – Demonstrate inherent optimal properties of artefact or provide optimality bounds on artefact behaviour
	Dynamic analysis – Study artefact in use for dynamic qualities (e.g. performance)
3. Experimental	Controlled Experiment – Study artefact in controlled environment for qualities (e.g. usability)
	Simulation – Execute artefact with artificial data
4. Testing	Functional (Black Box) Testing – Execute artefact interfaces to discover failures and identify defects
	Structural (White Box) Testing – Perform coverage testing of some metric (e.g. execution paths) in the artefact implementation
5. Descriptive	Informed argument – Use information from the knowledge base (e.g. relevant research) to build a convincing argument for the artefacts utility
	Scenarios – Construct detailed scenarios around the artefact to demonstrate its utility

As the design of the artefact goes through different stages, it may be necessary to use appropriate evaluation methods. The following approaches were taken into consideration while evaluating VisiLean.

6.1.1 Analytical

As mentioned by Hevner (2004) and shown in Table 29, the static analysis method of evaluation helps to evaluate/examine the structure of the artefact for static qualities such as complexity. Here a range of methods such as demonstrations, interviews and workshops with focus user groups were utilised to receive feedback while evaluating VisiLean.

While designing VisiLean it was crucial to understand whether the functionality and behaviour of the system conforms to the requirements (here from the context of production management system). User feedback gathering started very early in the process as key participating user groups were consulted through interviews, workshops and demonstrations. The feedback was then used to improve the system in an iterative and incremental way. This approach is also consistent with the agile project management technique used for software

development. The details of the feedback gathered during these sessions is provided in Appendix A and discussed further below.

6.1.2 Observational

The Case study method of evaluation through a pilot implementation on a construction project is very important as no other method provides more accurate results than conducting an in depth pilot implementation within business environment. In this case a motorway automation project was selected for pilot implementation described in section 6.3. The selection of the project was based on the following criteria:

- Access to project. As the client (a major public sector client in the UK) and the contractor were already participating in the VisiLean research, access to the project was made available. This is one of the crucial requirements in a design science project. Without access to a suitable project, it is not possible to conduct in-depth pilot implementation. It should be noted that a significant amount of “marketing” by the author was needed to secure the access to pilot project even as the stakeholders were participants in the project.
- Nature of the project. As VisiLean is a production management system that supports collaborative planning, detailed constraints analysis and integrates with a Building Information Model, it was necessary that the selected project was already following collaborative planning methods and had an operational parametric model (Building Information Model) available. Selecting a project where collaborative planning were not being followed would have been a significant challenge as significant training and cultural change are needed before collaborative planning methods can be used.

Following the pilot implementation, significant feedback was captured, which helped validate major concepts behind VisiLean design and the usability of the system within a “live” project environment. The design framework was updated based on the feedback received.

There were a number of limitations of the pilot project, mainly due to the factors that were outside the control of the author (internal organisational processes, availability of resources within research organisation, client organisation and the main contractors' organisation). One of the main limitation was that the pilot project initiated quite late during the research. As a result, while it was only possible to revise the framework (or system architecture) behind VisiLean, it was not possible to re-programme the prototype and re-implement to test it again.

6.1.3 Experimental

As shown in Table 29 there are two types of experimental methods used in design science, namely Controlled Experiment and Simulation. Both these methods are used to evaluate the newly designed artefact where it is not possible to conduct a live demonstration or implementation directly within the industry. As discussed below, both these methods were partially used while evaluating VisiLean in conjunction with other methods.

6.1.3.1 Controlled Experiment

The VisiLean system was tested regularly within controlled environment to check for performance against set parameters such as usability, individual functions (such as constraints analysis, integration with BIM, etc.)

6.1.3.2 Simulation

Sample Building Information Models and project management data were used to simulate the behaviour of Visi Lean.

The above-mentioned methods of feedback gathering and pilot implementation required significant interaction with participants from the industry. As development of an information system artefact is a complex and intense process, it requires constant evaluation against performance criteria. Therefore the research team used the experimental evaluation methods throughout the development to continually test the VisiLean system. In the controlled experiment methods, the research team constantly evaluated newly implemented functions and reported back any bugs or functional requirement change requests, which were then considered for development in subsequent

iteration of VisiLean. This development process has been described in section 5.6.

6.2 Evaluation Through Static and Dynamic Analysis

The evaluation process was carried out through focus group interviews, workshops and meetings with research participants. The information regarding the feedback process, including participant details, dates of workshops and meetings, and transcript/notes can be found in Appendix A.

As mentioned in Section 5.6, there were three major iterations in the development process, and frequent small iterations that took place during the development of the VisiLean prototype. The evaluation process started quite early, and contributed to the development of prototype throughout the process. However, for the sake of clarity this evaluation section is also divided to correspond to the three major iterations as described in Section 5.10 and shown in Figure 42. Here it should be noted that some features evaluated during each iteration were implemented within the same development cycle, while others were either implemented in the next development cycle (iteration) or left unimplemented, to be dealt with future development.

As the VisiLean prototype developed further, the number and complexity of features increased, however the evaluation has been divided against three major criteria/system functions, namely:

- User interface
- Production planning and control
- Product and process integration

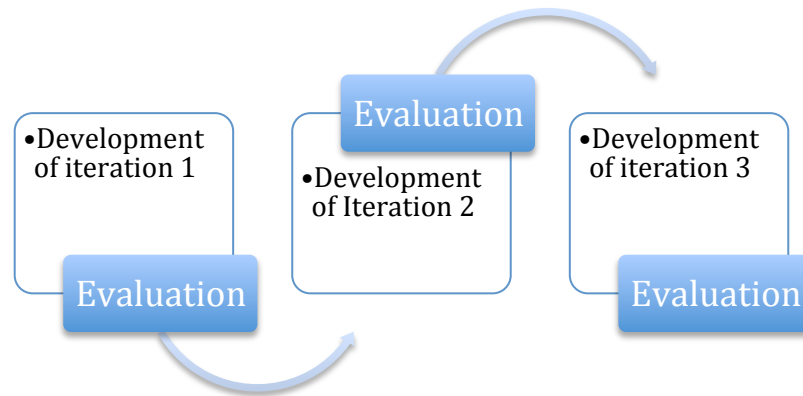


Figure 42. Development and evaluation cycle.

6.2.1 Iteration 1

The main goal of evaluation during the first iteration of the prototype was to validate the user interface and the main process for production planning and how the BIM model navigation will be implemented conceptually. As the prototype development had not advanced to a very functional or visual stage, this evaluation involved mainly internal participants (from Salford Centre for Research and Innovation) and some external participants who were experienced with production planning and BIM use on construction projects. Three internal research workshops were organised to carry out evaluation and two meetings with external participants were carried out.

6.2.1.1 User Interface

At this stage, none of the actual functions had been operational and only an application shell was presented to the participants. The goal was to get user feedback on the overall user interface design, including features such as placement of panels, planning interface, type of navigation between different parts of application and overall input/output during operation.

The users were presented with two main options; first option had two separate windows, one for production planning and another for BIM. While the second option had both interfaces integrated in the same application window that were positioned alongside each other, with production planning on the left side and BIM model on the right. The users opted for the second option with an integrated design, which enabled process and product visualisation from the same window. This decision was unanimous from all participants, as users wanted the facility

to view both process and product visualisations without having to switch windows. The participants also requested flexibility while choosing the integrated option so that the size of either panel could be adjusted to suit the nature of the BIM model and resolution of viewing screen.

In terms of other general user interface options, no major changes were requested, and the master-detail interface (where the details of any selected item would be displayed at the bottom of the screen), tabbed interface for planning workflow and general button layout were accepted as it is.

6.2.1.2 Production Planning

At this stage, the planning interface itself was not implemented but was presented in form of a process description, and a top-level process workflow diagram. Also, feedback regarding external planning and scheduling systems that the potential users would like to integrate with was sought. Here, the users preferred the freedom to create tasks directly in VisiLean as well as the possibility of importing an existing plan from major planning and scheduling systems. Also, the users indicated that in most cases the production team will receive a master plan that has already been developed so that would be the natural starting point for the workflow.

An activity breakdown structure having three levels; i.e. a phase, a task and a subtask were presented. The phase level would represent normally a work package (to be used during reverse phase scheduling), a task would represent a typical work activity at the look-ahead plan level and a subtask representing an activity that is further broken in sub-activities of manageable size that can be allocated to a worker or a team during a weekly execution plan.

6.2.1.3 Product and Process Integration

Similarly to the planning process, in the first iteration, none of the actual integration features had been present. There was a provision to import the model, however, no navigation, filtering or integration features had been implemented. At this stage, the users were asked to suggest what navigation features they would find useful, and also how they would like the product-

process integration to function (i.e. how to link tasks to the model elements, what information they would like to see on the model, etc.).

The users also provided feedback regarding the selection and filtering of elements in the BIM model so that the linking of tasks to elements is made more efficient. Essentially, the feedback received indicated that the system should provide a “tree” of element in a hierarchical structure to help with the selection.

6.2.2 Iteration 2

The second iteration was one of the intensive processes of development as most features were implemented during this iteration. Numerous demonstrations, workshops and meetings with focus groups were organised, and the project development team met frequently during this period.

6.2.2.1 User Interface

During the second iteration, the main features of the planning interface were implemented and evaluated. The main tabbed interface of the planning application, the general administration module and also the BIM model window along with its element filtering and selection tree and navigation tools were developed during this period.

The feedback regarding the tabbed interface was positive, and no change requests were received. The master detail interface was also generally well accepted. The use of colour coding to indicate the status of tasks and its synchronisation with BIM elements was also received positively during evaluations.

6.2.2.2 Production Planning

The production-planning feature in second iteration included the complete planning workflow with the Phase Planning, look-ahead planning and weekly planning modules. The constraints definition and management features were also demonstrated.

The overall feedback from the participants was positive, where the participants reported that they were satisfied with the planning workflow that the system presented. The constraints management capabilities of the system were also

reported to be very useful during the planning sessions. However, there were a number of issues, which needed attention that were highlighted by the users.

First of all, the issue of resource management was highlighted during evaluation. In the second iteration, there was no distinction made between consumable and non-consumable resources. In order to create a constraint, or in other words to allocate resources to tasks, each resource constraint had to be individually created in the Project Administration section. For example it was not possible to create a material resource type called Bricks where out of total 5000 bricks received on site, 2500 could be allocated to two tasks. Instead, two separate resource instances would need to be created each for 2500 bricks and allocated to each constraints. The participants found this aspect cumbersome and inefficient. Also, due to the distinction not being made between consumable and non-consumable resource, it was difficult to manage resources such as teams and equipment, especially when there are tasks competing for them. Participants indicated that they would like to see clashes between resource allocation highlighted in the system, where if a resource has been booked multiple times at the same time, the system would alert the user to correct the situation.

The second issue highlighted during the evaluation of second prototype was that of task hierarchies. In the first iteration a three level hierarchy of plan activities, where activities were divided into Phase, Task and Subtask was proposed. However, during the evaluation of the planning workflow, it emerged that there could be instances where plan activities at the subtask level need to be divided further into smaller chunks. This was due to the fact that many planned activities at the subtask level were too large to be allocated to a team or individual to be managed at the look-ahead or weekly level; were longer than a week (so they could not fit into the weekly plan) or they were not at a suitable level to be linked to a BIM element.

The third issue was regarding the organisation hierarchy. Similar to the task hierarchical structure, the first iteration proposed a two level organisational hierarchy, where tasks could either be allocated to an organisation or an individual. However, during the evaluation process, the participants highlighted

the need to allocate tasks to a team, which would consist of a group of individuals either from one or different organisations.

6.2.2.3 Process and Product Integration

The main change request during this evaluation was for more graphical information to be provided in the task window that was overlaid on BIM elements. There was a call to include more information such as visual information about the current status of the task, and the constraints that are associated with each task. The participants also indicated that they would like to manage constraints directly from this status window (i.e. to mark them as available), which should be in synchronisation with the planning interface.

The aspect of task hierarchies and the level of planning also affects the level of detail required from the BIM model in order to support product and process integration. For example, if a model is not sufficiently detailed, the team would not be able to link tasks at a lower level (i.e. weekly or daily) to BIM elements. However, this particular aspect is outside the scope of this research, and possibly even future implementation of VisiLean application in the field as in most cases the model would have already been developed. Hence, this aspect is covered through a set of recommended practice to designers in order to implement a Lean and BIM production management system on a construction project. This issue of level of detail required from the model(s) is also covered in the pilot project implementation.

6.2.3 Iteration 3

The third and final iteration (in the scope of the research project) mainly focussed on refinement and fine-tuning of features based on the evaluation during second and third iteration and also through the pilot project. Also, during this final phase of feedback, the users were encouraged to think beyond the prototype implementation and suggest features they would like to see in future implementations. For example, if they would like to see a touch enabled interface, development of a mobile interface to extend the use of the system in the field, etc. A number of features identified through this evaluation could not

be implemented due to lack of resources and time; they have been covered in Section 5.8.

6.2.3.1 User Interface

The first two iterations included panning, zooming and rotating features to help with the navigation of the model. During the third iteration, the users pointed out that having the facility to “walk” or “fly” around the model would make the navigation more efficient. Also, having these features will facilitate a better user experience if the system is implemented using a touch screen (as in the pilot implementation).

Separately, the users indicated that extending the core system through mobile applications that can be used from handheld devices such as Smart Phones and Tablet computers, will improve the overall usability of the system and help keep the system updated frequently.

6.2.3.2 Production Planning

One of the key requirements to emerge during evaluation at this stage was about booking of non-consumable resources such as specialist teams and equipment (such as crane, fork-lifts, etc.). Users pointed out that one of the biggest contributing factors for the delay on construction sites is multiple booking/allocation of a particular resource. Specialist equipment such as Cranes are normally booked by the hour to particular tasks. Similarly when the site is congested or located on different levels, space needed for construction operations could also be a critical constraint and should be booked in advance to reduce clashes during execution. As a result, a booking system was recommended for such resources.

Also, to minimise clashes between competing tasks, whenever a resource was allocated to multiple tasks the system prompts the user and also displays a graphical symbol next to the task (in both planning and BIM window) so that such clashes can be dealt with swiftly.

During the first two iterations of VisiLean, the users had to first create a plan and then manually select the tasks from a look-ahead or a weekly planning window,

which would then be added to the respective plan. Users indicated that this process added unnecessary steps and requested automatic creation of a look-ahead and weekly plan based on the date (and a look-ahead window in case of creating a look-ahead plan).

In the case of the look-ahead plan, the system should automatically populate the plan with all the tasks scheduled between those dates. During the collaborative sessions, those tasks, which cannot be “made-ready” within the look-ahead window, would be removed from the plan. Similarly, the weekly plan should be populated automatically of all the tasks, which are free of constraints.

6.2.3.3 Process and Product Integration

The first two iterations of the software had one-to-one mapping between tasks and BIM elements. Hence it was not possible to select multiple tasks, which would be highlighted on the BIM window. This somewhat limited the functionality to carry out constructability review and visualise the sequencing. This issue was highlighted by the users, and the possibility of multiple task visualisation on BIM window was requested.

Also connected to this feature, was the possibility to carry out 4D reviews of look-ahead and weekly planning schedule, or for any selected tasks was also requested. This feature would enable a 4D style animation of selected tasks to help understand the sequence of tasks and at the same time visualise their current status (i.e. ready, non-ready, in progress, etc.).

Task creation in first two iterations was made possible either via importing an external plan, or creating tasks within VisiLean planning window. However, a new feature was requested, whereby a user would be able to create a task by selecting a BIM element.

6.2.3.4 Reporting

As the core system features were still being developed, the first two iterations of the software did not implement any reporting features. However, in the third iteration some basic reporting features were implemented. These reports enabled generating a PPC, reasons for non-completion and a task-list ordered by

a subcontractor or a data-range automatically from the system. PPC and reasons for non-completion are two of the core lean reports and enables continuous process improvement.

As VisiLean captured a significant range of current production data, the users requested a dashboard interface where real-time information about production can be graphically displayed to enable project managers and other stakeholders respond to the progress and take necessary actions appropriately.

A3s reports are also very important features in lean production, as they enable efficient problem solving in the field. Users also requested automatic generation of an A3 report that could be customised by the project manager to display various production related information, including PPC, reasons for non-completion, performance of constraints analysis, etc.

6.3 Pilot Project

In design science, one of the highly rated methods for evaluation is direct implementation of the newly constructed artefact in a real-life commercial environment such as the case study or field study method as mentioned in Table 29 by Hevner (2004). Due to on-going collaboration with a number of construction organisations and clients, it was possible to organise a trial implementation/demonstration of VisiLean, where real project data was imported and simulated and demonstrated to the project team to receive their feedback. As such the pilot project did not involve actual use of the system during collaborative planning sessions, but involved detailed demonstration of VisiLean using actual project planning and BIM information. The pilot project was commissioned by the client organisation, however the main stakeholders during the execution were the main contractor and the design organisation. In particular the following individuals took part in the trial:

Main contractor:

- i. Group Business Improvement Manager
- ii. Project Manager
- iii. Lean Project Planner

- iv. Project supervisor (Ductwork)
- v. BIM Manager

Designer:

- i. Managing consultant
- ii. Chief Engineer
- iii. Senior Group Engineer (Design, BIM support)

The main selection criteria applied while selecting a pilot project are described below.

- i. **Following collaborative planning process:** As VisiLean supports the Last Planner System™ of production planning and control, it was thought necessary that the selected project should also be following a collaborative planning process. Due to the short time scales involved, and limited resources, training the project team on collaborative planning practices if they are not already following them was thought to be a difficult aspect. It helped significantly that the client organisation (who sponsored the project) had mandated the use of collaborative planning processes on all their new projects, and had already trained their first tier supply chain. Also, the main contractor on the project was also quite familiar with the lean collaborative planning and had been implementing them on many of their projects for at least past five years.
- ii. **BIM model availability:** VisiLean integrates the BIM model with the production planning process; hence a model of the project was a requirement. This aspect was challenging as the client was the Highways Agency in the UK, and BIM was not yet very commonplace in the infrastructure sector. Only the major schemes would have a 3D model, and even then it was not certain that the model available would be fully parametric. However, a scheme was identified that had a model available which had partial parametric capability. Further details regarding the model are found below.

The following section describes the project and the implementation process in detail.

6.3.1 Project Specifics

6.3.1.1 General Project Details

The main project was to install automated traffic control gantries on a major UK motorway. The client was the UK's Highways Agency, and the total project duration (as planned, starting from January 2012) was approximately 26 months.

The main purpose of this project was to reduce congestion and improve the flow of traffic, especially during the peak hours. This would be achieved by imposing variable mandatory speed limits and allow the use of hard shoulder (emergency lane at the side of the motorway) as an extra traffic lane. The variable speed limit imposed will be displayed on the newly installed gantries, which will also house automated speed cameras to enforce the limit. Figure 43 shows how the managed motorway system works in its entirety. According to the Highways Agency the main benefits of this system are:

- Additional capacity for vehicles
- Improving the detection of incidents
- Improving the response to incidents
- Helping to alleviate congestion
- Reducing delays caused by incidents or congestion
- Piloting new and innovative concepts
- Targeted solutions to specific problems

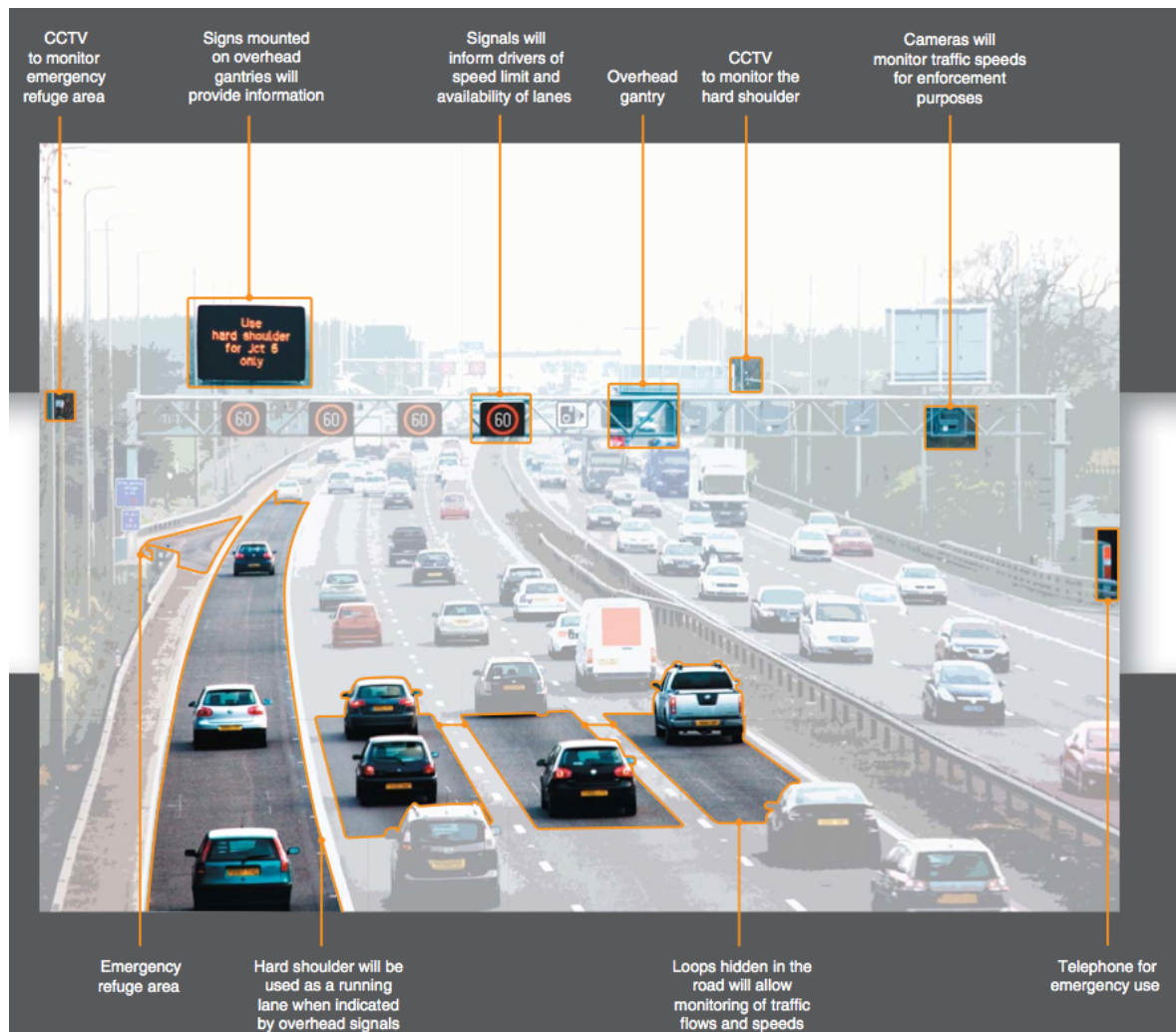


Figure 43. Managed Motorway System (Courtesy of Highways Agency, UK).

6.3.1.2 Stage of the Project

When the implementation started, almost 80% of the project scope was complete. The main activity that was left to complete was cable ducting and installation. Hence, these activities were the main focus of the pilot project, and only the tasks related to ducting and cable installation were focussed upon during the implementation.

6.3.1.3 Existing Systems Being Used

Lean Process/Production Management: As mentioned above, the project was already following the collaborative planning process. The look-ahead window was 2 weeks long, and the project team also met every week for the commitment planning session. There was also a “daily huddle” at the end of the day to discuss the progress (for that day) and also to discuss the next day’s tasks. There was

however one variation, during the look-ahead planning meetings, instead of doing a detailed constraints analysis, the site manager delegated the responsibility of removing the constraints analysis to each team. This followed on with the assumption that if the team leader commits to a task, the constraints have been (or will be) removed in due time.

The project used a shared meeting space to organise collaborative meetings, where progress charts were also displayed, along with the PPC and a “Concern and Countermeasure” board. The “Concern and Countermeasure” board can be likened with the constraints removal process; here each concern (i.e. constraint) related to the project was listed along with the responsible person to remove that constraint and the status (i.e. whether it has been removed or not). This room also hosted a number of large-scale drawings with visual tracking of activities (colour coded to demonstrate completed, on-going and future activities).

The team used Primavera Project Planner as the chosen project planning tool to carry out master planning activity. For collaborative planning, Microsoft Excel was used, where each task manager had developed his or her own project planning worksheet. Bentley ProjectWise was used as a project information management system (project extranet), which stored relevant project information and also provided shared access to the project team.

BIM Model: The project had been designed using Bentley MXROAD, which is a software for road design. Although it is a capable road design software that enables 3D model creation, it is however a string based design software, which does not allow for creation of parametric objects. As a result, the designer used a special software process to export the model in VRML that created solid objects from strings, and then added parametric information manually. This however, posed a challenge in terms of the pilot implementation, as VisiLean relies on the parametric objects in the model in order for them to be linked to the tasks in the planning window. Hence, the model had to be modified accordingly so that it included identification information for individual objects.

Also, as the model was exported in VRML format and then imported in Navisworks, the hierarchy of model objects was not very clearly present in the model. The VisiLean system depends on this object hierarchy to build a tree of elements that helps in selection of objects, which can be easily linked to tasks. Due to this lack of hierarchy, a custom object tree had to be created in VisiLean.

The collaborative planning meeting space also housed a large screen (72") SmartBoard that was connected with a laptop computer running Autodesk Navisworks 2012. This SmartBoard also offered touch capability, which were useful in navigating the model by using either the fingers or the SmartBoard pen.

6.3.2 Scope of the Pilot

Due to resource constraints and time limitation, the overall duration of the pilot project was 3 months. However, only two months were available for actual implementation due to planned and public holidays, and also due to the desk based research and preparation work involved. When the pilot project started 80% of the construction work had been completed and only ducting and communication installation activities were remaining. Hence the pilot project focussed on implementation of these activities. The following project processes were within the scope of the pilot.

- i. Modifying the BIM model
- ii. Training the team in use of VisiLean
- iii. Importing tasks in VisiLean and getting ready for the pilot
- iv. Supporting 2 look-ahead planning sessions
- v. Supporting 3 weekly planning sessions
- vi. Supporting 3 daily planning sessions
- vii. Receiving feedback from users, identifying what worked and lessons learnt
- viii. Identifying model requirements for future implementation of VisiLean

The main objective of the pilot was to receive feedback from those involved in the planning session on VisiLean to validate the prototype. In parallel, it was also important to identify what are the other requirements, i.e. from process, training and technology perspective that have to be met in order to implement a

production planning tool such as VisiLean. The following section describes the pilot implementation process in more detail.

6.3.3 Implementation Process

The implementation process consisted of three main stages as mentioned below, namely, preparation, implementation and feedback gathering. As mentioned above, due to VisiLean being research software and in the prototype stage, it was not possible to use it during actual collaborative planning sessions, as it would increase the risk to the project. However, a trial implementation, which incorporated the actual project BIM model and collaborative plans of the “duct installation” activity was organised. Also, collaborative planning sessions were simulated within the system, including look-ahead and weekly plans, constraints analysis and management, task management (including starting, stopping and completing tasks), and some reporting functions. The feedback was gathered during each demonstration sessions, which was taken into account partially during the development process (as outlined in three iterations) and the features, which could not be implemented were documented for future development.

6.3.3.1 Preparation

In order for the VisiLean software to support the collaborative planning process for the pilot project, some modifications were required. Previous to the trial, VisiLean had predominantly been tested to display and manipulate building models, which are relatively compact and easily navigable. The trial project by contrast was spread over a large area, and consequently the associated model is commensurately large in dimension. Given the extensive and linear nature of this model it became necessary to implement a zoom feature that aligned the viewpoint direction and scale with a specified model element. This allowed for rapid focus on model elements pertinent to a given task without the necessity for extensive panning and zooming which can easily result in losing ones bearings in the model 'space'.

Another significant issue with the model for the trial project was the lack of a natural candidate for model element 'identity' in technical terms. Resolving this

issue, involved work on the part of both the VisiLean team and the project's BIM modeller (who belonged to the Design organisation). Firstly, the modeller assigned a unique label to model elements that were of interest (in this case the ducting and communication equipment), aggregating a number of geometric entities into a pseudo 'object' analogous to the type one might expect to have access to in a building construction BIM model. Once this task was complete, the VisiLean team was then able to implement a data provider that allowed the software to interpret the provided identifiers and map them into selections on screen as required.

Once the model was properly imported and navigable within the VisiLean system, the plan was manually input in the phase planning module. The planning tasks had to input manually as they were created in custom Excel spread sheet used by the contractor. The plan tasks were then linked with the model elements. Once the tasks and BIM elements were linked the system was demonstrated to the contractor's lean planner and process improvement managers for their approval to try the system during their next look-ahead and daily planning sessions.

Apart from getting the model ready and importing in VisiLean and to create tasks and add their details in the system, a number of meetings and demonstrations were organised to familiarise the team with the VisiLean system. Initially, the demonstrations served to get the "buy in" from the team and to capture their feedback on the system, which also helped to identify their requirements. Subsequently the meetings were organised to demonstrate the progress with the imported model and discuss specific changes that were needed to be made.

6.3.3.2 Implementation/Demonstrations

The first task during the VisiLean pilot was to understand the existing lean and BIM processes that the main contractor had been following and to identify their major requirements from VisiLean. The first meeting was held with the Business Improvement Manager, who provided information regarding their current processes, and feedback regarding the applicability of VisiLean to their

collaborative planning process. Figure 46 shows the VisiLean researcher demonstrating the system to the project team.

The company had been using their own collaborative planning approach, where there were four main planning levels, i.e. master planning, stage planning, look ahead planning and weekly planning. Also, the company used a visual measure called “concern and countermeasure” board to manage some of the constraints.

The main feedback received during this meeting was that the construction organisation had been looking for a solution which helped integrate/synchronise a number of information sources such as safety management, field inspections, knowledge management to the production management process. It was also mentioned that identification of temporary work areas/zones and treating them as constraints would also be very useful. This would ensure that there are no more than a certain maximum number of workers sharing the space and that there are no conflicts in space utilisation. The Business Improvement Manager also expressed interest in linking daily progress update photographs with the VisiLean system (in both the planning and modelling windows).

Subsequently, a meeting with a senior director within the Highways Agency was organised. The main purpose of this meeting was to demonstrate the system, communicate the main project objectives and obtain a senior level “buy in” not only just for the pilot project, but to the overall integrated lean and BIM process within Highways Agency. Following the demonstration the director approved the pilot and agreed that following the outcome of this project, the Highways Agency will consider the integrated lean and BIM approach for their subsequent projects.

Following the approval, the VisiLean demonstration/implementation consisted of a series of planning sessions where the VisiLean team facilitated the demonstration of the system and simulated the collaborative planning sessions using actual project information. Table 30 provides details of the implementation/demonstrations sessions, which were carried out during the pilot. The VisiLean team was present during all sessions.

Table 30. Schedule of the VisiLean demonstration and implementation sessions.

Date	Session Details	Persons involved
6 March 2012	Initial discussions related to selection of the project and “selling the idea”	Business Improvement Manager (main contractor)
26 April 2012	Initial demonstration meeting with the project team	Business Improvement Manager, Lean Planner, BIM Technology Support Engineer, and a Senior Design Consultant
8 June 2012	A demonstration meeting with the Director of Highways Major Projects	Director of Major Project
5 Sep 2012	Demonstration meeting to the design team to identify the best way forward for the pilot project and also to outline the changes required to the project BIM model	Project’s BIM Designer, Senior Design Manager and Senior Design Consultant
21 November, 20 December 2012, 17 January 2013	Demonstration of VisiLean and simulating the collaborative planning session to project team members	Project lean planner, Business Improvement Manager, Assistant Lean Planner, Section Engineer, BIM Technology Support Engineer



Figure 44. Discussion during the final feedback session.



Figure 45. Final Feedback Meeting at the main contractor's Office.



Figure 46. VisiLean researcher demonstrating the system.

6.3.3.3 Feedback from sessions

As mentioned above, several sessions where VisiLean system was demonstrated to various members of the project team were organised. Prior to each meeting, the VisiLean system was prepared by importing the project BIM model and by importing project plan. During the meetings, the VisiLean system was run and a collaborative planning session was simulated. During the demonstrations, notes were taken, which were then analysed. A record of these feedback sessions and their outcome is presented in Table 31.

Table 31. Feedback from pilot demonstration and outcome

Session	Feedback	Outcome
05/9/12	<p>In this first session the BIM model was imported to VisiLean and tasks related to installation of ducts were discussed. As the project involved laying communication infrastructure through ducts on two major motorways, it also passed through the intersection. Due to the added complexity of the intersection, it was identified that the tasks around the intersection are the most difficult to visualise, especially when they have are interconnected. It was suggested that the VisiLean system would be especially useful in such complex situations.</p> <p>Upon demonstration of the system, the section engineer in charge of the ducting tasks highlighted the current problem of having to “chase” different systems to get production related information. Especially, the information related to task management, i.e. status of tasks in production (started, stopped, completed, etc.) and also reasons for deviation from the schedule. The section engineer highlighted that a system such as VisiLean will help overcome that problem by having all information in one place. It was recommended that a feature should be added whereby notes can be added to tasks and stored for future auditing.</p> <p>The section engineer also highlighted the usefulness of a system such as VisiLean during daily planning sessions, where they occasionally use a large touch screen and project the plan (in Excel) and the BIM model.</p> <p>A number of issues with the model were identified at this meeting, which are discussed 6.2.3.1 above. These were due to the model not having full parametric capabilities.</p>	<p>1. A feature was added in the task management window where notes can be added to tasks and stored for future reference.</p> <p>2. Changes needed with the model were noted so that it can be imported in VisiLean.</p>
21/11/12	<p>When the model was imported in VisiLean and a custom selection tree was built, in the next demonstration a look-ahead plan was imported and the model was also available. It was found that due to the lack of hierarchy in the model, there were over 1100 elements just in the ducting work package. This made it extremely difficult to find the relevant BIM element during the planning meeting while trying to link them to the look-ahead plan. Two suggestions were made to overcome this problem. First suggestion was to only include model elements, which had matching tasks in the look-ahead plan. This was a temporary short-term fix and didn't solve the problem going forward. The second suggestion was to provide a search box, which would enable searching for elements using a string. This was potentially a long-term solution, however, but would need significant changes to the VisiLean system.</p>	<p>It was decided edit the model import file in VisiLean so that only those elements with matching tasks in VisiLean would be displayed in the selection tree. This made it easier to link them to the planning window.</p>

Session	Feedback	Outcome
20/12/2012	<p>Once the model was updated to include the limited amount of ducting elements, the planning tasks were linked to the model and their respective constraints were added. At this stage the VisiLean system had the two week look-ahead plan and two weekly plans added to the system and all the tasks were linked to the BIM model.</p> <p>During this session, the Business Improvement Manager asked if it would be possible to get an “overview” of task statuses in the BIM window. At this stage the VisiLean system only has a “one-to-one” mapping, i.e. only one task/subtask can be selected and respected BIM elements viewed in the BIM window. However, to get a quick overview of the current production status, this would not be very efficient. This requirement was recorded, however due to significant amount of work needed, it was not considered for implementation.</p> <p>The Business Improvement Director also highlighted the benefit of using VisiLean as it can potentially be used as a system that helps “aggregate” all relevant production related information. Although, currently in the VisiLean system this information has to be input manually, going forward the idea is to dynamically link information such as procurement and cost estimating and quantities through relevant information systems.</p>	<p>The feedback received from this final session was used to draft recommendations and document the perception of the project of VisiLean, which were then submitted to the Highways Agency. Due to the limitation of time, it was not possible to make further changes to the VisiLean system and re-implement it to this project. However, some of the features, which were deemed important have been considered for future implementation in 5.9.</p>
17/1/2013	<p>Figure 44 and Figure 45 show the VisiLean system demonstration and discussion during the final session. In VisiLean, the final session included the complete two-week look-ahead plan and two weekly plans, along with the links with the BIM model elements. Detailed discussions took place during this session and significant feedback was received relating to the VisiLean system and also what measures should be taken to implement a system such as VisiLean on future projects.</p> <p>The most important discussion revolved around how to create a “common language” across the transport industry so that synchronising the planning tasks and model elements would be a relatively efficient process. As witnessed in VisiLean, almost 30-40% of the effort during the pilot project was dedicated to making changes to the model, first to import it in VisiLean and secondly to link it to the project plan. By creating a commonly accepted method of structuring the model and also preparing the project plan, it would make it easier to link tasks to model elements. Also, the importance of having a fully parametric model, where a well-defined hierarchy of objects is available, was emphasised.</p> <p>The need to involve main contractor during the design process was also highlighted. The members present during the session felt that at least the project planner and engineering manager should be involved during design to provide knowledge of constructability aspects and to ensure the model</p>	

Session	Feedback	Outcome
	<p>is developed to a sufficient level of detail so that it can be used properly during the production stage.</p> <p>From VisiLean system point of view, a number of issues were raised. In the current iteration, the VisiLean system did not have any notifications for pending tasks or “unresolved” constraints. The site team suggested that the relevant members should be sent a notification at a set time prior to the weekly planning meeting, reminding them if any of their tasks have constraints, which are not yet resolved. It was also highlighted that an overview “heatmap” in the BIM window, showing the status of the project at a glance should be provided. This means a colour-coded model showing the relevant production status of the tasks.</p> <p>The Engineering Manager also highlighted the need to have cost and quantity related information linked to the tasks, as this information is very regularly needed and if linked, could help with automated generation of a number of reports.</p> <p>The project team reported a current problem with the planning process in VisiLean, which was related to the weekly planning module. In the current iteration, the VisiLean system would not let the user select a task for execution if it has a predecessor, which is not yet complete. However, the team highlighted a scenario, whereby a sequence of interrelated tasks, which are all scheduled for execution for the same week (and otherwise free of constraints) are there in the look-ahead plan. This was identified, and it was decided that the VisiLean systems should allow releasing such tasks to the weekly plan.</p> <p>The project team found the VisiLean feature of flagging “conflicting resources (constraints)” very useful. As on the current project, one of the formwork subcontractor regularly assigned the same resource to multiple tasks (which are managed by different section engineers), ultimately leading to non-execution of at least some of the tasks. As the current planning is done using Excel spreadsheets which are not linked with each other, this is not detected (unless discussed directly during a meeting). It was mentioned that by clearly showing a conflict between the allocated resources before execution starts would prevent such conflicts and improve the PPC.</p> <p>Overall the feedback was positive and it was recognised that VisiLean bridges a distinct gap in the market, by providing a production management system for the project. It was also suggested that the VisiLean interface should be as simple as possible for it to be used by site personnel and consistent with the collaborative planning process. It was also mentioned that the VisiLean system has a potential to reduce the amount of rework needed while maintaining separate systems for Lean and BIM, and also separate systems to manage the production processes (such as planning spread sheets).</p>	

6.3.3.4 Lessons learnt and summary of the pilot project

The main lesson learnt during the pilot was that for any software system such as VisiLean to succeed, it is important to not only have the BIM model in place, it is equally important for it to be developed with proper parametric capabilities and to an appropriate level of detail. It is also important to note that without proper collaborative planning in place, i.e. without detailed constraints analysis, the effectiveness of the VisiLean (or a similar) system will be reduced.

Another major consideration that emerged during the pilot was about the quality and depth of information. For VisiLean to succeed, constant updating and input of relevant information to the system is required. Without the daily updating of system, the system won't function properly and provide inaccurate information, which could even be detrimental to the overall efficiency of the production system.

All the project team members unanimously agreed that for a system such as VisiLean to succeed and being used on the project, the user interface has to be very simple and intuitive. It was also suggested that providing a user interface, where it can be navigated using touch gestures will be better. Also, the proposed mobile interfaces (for smart phones and tablets) were welcomed.

Overall, the users received the VisiLean system in a positive way, and found it to be a supporting system that could be utilised after the suggested improvements were made, and when the required features could be added.

6.4 Current state of development and its critical analysis

Table 32 provides a critical evaluation of VisiLean prototype in its current form based on the relevant evaluation criteria mentioned by Hevner (2004) and feedback received (through three iterations).

Table 32. Current state of development and its critical analysis.

Evaluation Criteria	Synthesis of feedback	Critical Analysis
Functionality	<p>The current function set is good to begin with, especially as it provides a way to tackle Last Planner™ workflow in a systematic way, and helps carry out constraints analysis and identifies conflicts between resources. The visualisations of model and production status are also useful functions.</p> <p>A number of additional functions are desired, such as the cost and quantity information, analysis and reporting in form of a dashboard, deeper integration with BIM (by way of simulation of look-ahead and weekly plans and multiple task selection).</p>	<p>Overall, the current VisiLean system is only the beginning and lacks a number of useful functions. It was designed as a demonstrator of an integrated Lean and BIM system that could help the “Last Planners” with site based planning and control functions. Although it succeeds in that, a number of additional functions will make it stronger and useful on site.</p>
Completeness	<p>In its current form VisiLean is not a complete system, as the above-mentioned features are missing. It is a starting point on which other functions could be added. However, for organisations using just Post IT™ notes and paper-based workflow, it provides an opportunity to rethink their approach and have a system that integrates product and process views, i.e. through Lean and BIM.</p>	<p>As the feedback suggests, the current system does not provide a complete set of functionality but demonstrates the functionality a potential lean and BIM system could have and justifies the research themes of integration, synchronisation and visualisation.</p>
Performance & Reliability	<p>As VisiLean is still in a prototype stage, it is too early to comment on performance on reliability. It is not a reliable system in its current form as it crashes often and has inconsistencies in behaviour. Performance with the tested dataset has been found to be satisfactory, with information display and visualisation being instantaneous and no lags in model visualisation either. However, the prototype has not been tested with a large project and a complete project plan (i.e. end-to-end), which would push the system to its limits both hardware and software wise.</p>	<p>Further testing, development and pilots would improve the system from its current stage. It is not a commercial grade system and still contains a number of bugs and suffers from frequent crashing (unexpected shutdown, corruption of data, etc.). However, it has not been developed with substantial resources and is meant as a proof of concept.</p>
Usability	<p>Here, usability is understood as a quality of the system that makes it intuitive and “easy to use” for the intended user. The intended users are members of the construction team on site. The VisiLean</p>	<p>Although usability has been one of the key factors driving the VisiLean design, it has not been possible to implement all the desired features due to resource</p>

	<p>prototype, when shown to the user base was found to be intuitive in use and not a significant amount of training had to be provided before users understood the functions behind the system. However, a number of issues remained to be resolved. For example, a Post IT™ note type Lookahead and Weekly Planning interface that could support collaborative planning (in its current form) has not been implemented. If implemented, this would mean that users of the traditional Last Planner™ system would find it highly intuitive to use and its collaborative appeal would improve.</p>	<p>restrictions. One of the main features is the “touch friendliness” where the system could be driven by using just fingers (rather than traditional keyboard and mouse interface) hence could easily be used on a touchscreen. In its current form the dialog boxes are a little small and spaces between task grid (or lines) not sufficient for a touch based experience. Future versions and research should focus specifically on the user interface improvement aspects and improve the usability further.</p>
Fit with organisation	<p>Although the system in its current form would appeal to most of the project and management team, there are still a large number of workers who are not ready to use a computer-based system for collaborative planning. Also, a number of internal champions believe that having a computerised system for production planning and control and visualisation of design adds to variability in the system (due to possible downtime and reliability and user acceptance issues), hence affecting the productivity of the team in general. Hence, a user buy-in and an extensive change management effort are needed before the VisiLean system could be implemented.</p>	<p>It is well understood that any new major technology or process implementation requires a substantial process change within an organisation. Depending on the current maturity with Lean and BIM within a target organisation, a potential VisiLean implementation would also need an element of change management and user training before it is accepted for use. However, given the current “drive” especially through the UK government’s BIM mandate and Latham and Egan’s recommendations to implement Lean, majority of the organisations are already implementing or considering implementation of both these practices. This would potentially support the case for VisiLean (or a similar system’s) implementation.</p>

Table 32 provides a critical analysis of the current state of development within the evaluation framework suggested by Hevner et al. (2004). It emerges from the critical evaluation and through own interpretation that VisiLean is still an incomplete system with several shortcomings, such as lack of distributed access, lack of cost and quantity information, and that there is scope in developing VisiLean further. This aspect is further explored in Section 5.8 and 5.9, (unimplemented features and plans for future development).

Separately, the evaluation process itself had its limitations during VisiLean research, to be outlined next.

As discussed in Chapter 5 and 6, the evaluations were carried out in three separate yet interconnected phases, namely

- a) In process evaluation – i.e. constantly evaluating the prototype as it was being developed. This was mostly done by the VisiLean development team internally.
- b) External evaluations through interviews and workshops and a limited pilot – these evaluations were carried out with construction professionals by demonstrating the software and asking for their feedback.
- c) Final critical evaluation against criteria set by Hevner et al. (2004) and own reflection on the artefact as it has developed, as reported in Table 32.

Although the evaluation in most parts went as planned, the pilot project did not complete as originally hoped. This was due to the problems highlighted in Chapter 6, mainly as there were issues with the BIM model that had to be corrected, which affected the time available to carry out a full pilot. Hence, instead of working with actual project data and supporting live planning sessions as originally planned, only simulation of project data and planning meetings could be carried out.

Nevertheless, the achieved level of evaluation is in broad alignment with the views presented on evaluation in the Design Science Research methodology literature such as Hevner et al. (2004) and Lukka (2003). Scholars have mentioned that rigorous evaluation methods are extremely difficult to apply in

design science research (Hevner et al., 2004). Moreover, it is not possible to generalise the evaluation to other projects if the evaluation has only been carried out on a single project (Markus et al., 2002).

6.5 Summary

Evaluation is one of the most important aspects of design science research as the usefulness of the artefact depends greatly on the quality and depth of evaluation. From that perspective, this research benefited from a large group of participants who took active part in all aspects of evaluation and provided their valuable feedback. The research also benefitted largely from a funded pilot project, where it was possible to implement VisiLean prototype on an on-going construction project as reported in 6.2

In general, the feedback received during the evaluation was positive. One of the factors in measuring the success of design science research according to Kasanen et al. (1993) (this is also called a “weak market test”) is when a manager agrees to try/pilot the solution. In the case of VisiLean, a number of organisations were willing to pilot it on their on-going projects, and one such pilot was carried out during the scope of this research. Two further pilot projects have been identified and potentially will be carried out in future. This partially demonstrates the effectiveness and practical value of VisiLean solution.

During the demonstrations, the relevance of the VisiLean system and its potential to support productivity improvements were highlighted by most participants. However, there was also some scepticism expressed by the participants regarding the introduction of an “untested” technological solution to the production process, as this could lead to increased variability and risk in the production environment. This was also due to the fact that many of the participants were familiar with the lean production processes and feared that VisiLean may hamper/affect the collaborative nature of the lean projects. However, as VisiLean does not aim to replace the collaborative nature of the planning process, but tries to augment/support it, the scepticism was reduced and the acceptance of the system grew considerably.

Also, as outlined in the critical review of the current development, some of the features requested by participants were missing from VisiLean prototype. These features would certainly add value to VisiLean and can potentially make VisiLean a capable production management system.

As mentioned in Chapter 5, the design, development and evaluation processes are iterative and incremental, and further VisiLean development will continue to follow the same pattern. However, it is anticipated that in future, the evaluation will be based around the pilot projects where practical applicability of features will be tested on live environment as new features are added to the system. In its current form, VisiLean should not be taken as an “industrial strength” product, but a research prototype with limitations, which has been developed to demonstrate the benefits of an integrated lean and BIM system.

7 Discussion and Conclusion

This Chapter provides an overview of the research and main conclusions. The chapter begins with a discussion on main findings for each key stage of the research and follows on with a summary of main conclusions and direction of future research.

7.1 Discussion

This discussion is about the overall research and not the research artefact, which was discussed in Chapter 6. The main aim for research was to improve construction management through application of Lean and BIM. Additionally, it was hypothesised that the deficiencies of the production management systems could be addressed through a software solution that integrates process and production visualisation. The main problem being addressed was grounded in practice and emerged from the author's own observations but also had potential for theoretical contribution.

Although the overall research experience has been positive, a number of problems were encountered during the research. The most significant problem can be considered as the limited number of alternative solutions, which could be considered or developed for VisiLean. This means that further possibilities of experimentation with a wide range of aspects such as user interface, workflow, reporting, etc. exist that can be considered for future research.

The main observations from research are presented in three separate sections, research method and problem identification, research solution and research evaluation.

7.1.1 Research Method and Problem Identification

According to Lukka (2003) and Hevner et al. (2004), selecting a practical problem that also has relevance for the industry and finding long-term partnership/cooperation with organisations are important aspects of design science research. The perceived relevance and importance of the solution and research itself within the participating organisations provided significant motivation to the author.

The problem selection and its relevance in real world are two important aspects in design science research method. The author had a first hand knowledge of the problem area, which helped considerably in understanding the context of research and also while evaluating alternatives during design and development.

As the research was being conducted within a well-established research centre that had strong ties with the industry, it was possible to receive feedback from a large number of practitioners throughout the research process. The design science method provided a flexible yet a structured approach, where a number of evaluation instruments were used throughout the research, including focus group interviews, workshops, meetings and finally a pilot project to gather feedback and evaluate the research.

The evaluation process also encountered a number of difficulties, especially during the pilot project. The main lesson learnt was that technological solutions (such as VisiLean) require careful consideration of people and processes within the target organisation and it is very important to plan the implementation in advance. The implementation of Lean and BIM have implications right up to the design process, where the BIM model has to be developed at the right level of detail and having the correct object parameters and structure. Also, the use of appropriate BIM tools and mutually compatible platforms is one of the significant considerations.

7.1.2 Design and Development of the Research Solution

Lukka (2003) emphasises the importance of this stage, as the innovative solution to be designed is the core aspect of the research, and it is important to distinguish the constructive and innovation oriented research from a simple transfer of off-the-shelf solution. Here, the research solution was developed in three interconnected stages, narrowing down the solution areas, developing a solution framework and designing and developing the solution. First the solution area was narrowed down to lean construction and Building Information Modelling, as it was identified that both process and product management are important from production management perspective. Following the identification of broad solution areas, it emerged that the synergies between

Lean Construction and BIM span the entire lifecycle of the construction process, and there are significant interactions between Lean and BIM during the production management stage. Empirical evidence emerged supporting these synergies, which is highlighted in the 56 individual interactions in Table 15. This conceptual framework of interaction between Lean and BIM can be considered a high level conceptual framework that contributed to the development of the VisiLean system. This led to the next stage of development of the high level framework based on which the core requirements for VisiLean were developed. Subsequently, a conceptual solution in form of the VisiLean prototype was designed and developed through three major iterations.

The development process was a highly collaborative process where the author engaged constantly with the industrial participants and the programmer, evaluating the solution at each stage and carefully considering the next steps to be taken. The agile development method that was selected during the development of VisiLean solution was suitable given the small team and its ability to support rapid prototyping and evaluations.

During the development of VisiLean, additional requirements emerged, for example support of additional workflows such as quality, safety and cost management. Although these were not originally thought of as core functions of VisiLean, it was recognised that the potential users (research participants) would value them significantly. Also, it emerged during the development process that a system such as VisiLean could also support creation and reuse of collaborative knowledge that is integrated within the production system. Overall, VisiLean prototype encompassed features that would support the product and process integration, visualisation and synchronisation through the support of the Last Planner™ workflow and integration with BIM.

7.1.3 Research Evaluation

Evaluation is considered as an integral part of the design science research, where both the newly constructed solution and the process of implementing it in the target organisation are tested. As reported in Chapter 6, a large number of

evaluations took place during the lifecycle of research, as the solution area, top-level research framework and each development iterations were evaluated.

One of the most critical aspects was that to make the production management system available/accessible to the construction team, and to ensure that it is simple and intuitive in nature so that it is accepted by the site teams. The VisiLean system successfully demonstrated this, and it can be said that it was successful in solving the practical problem that was originally set out.

It emerged during evaluations that a solution such as VisiLean had its uses for a number of organisational roles on a construction project. For example, it appealed to both middle management (such as project managers, business improvement managers, BIM managers) and site-based personnel (site managers, site supervisors, foremen, etc.). Several of these participants highlighted the immediate need for such a solution in the industry after demonstration and mentioned that no parallel/similar solution yet exist in the market. Also, as mentioned in Chapter 6, several requests for testing the solution in participants' organisations were received, which in itself partly validated the research idea and solution. However, a number of shortcomings of the VisiLean prototype also emerged, and a number of features remained unimplemented due to time and resource shortage. Also, the final evaluation in the pilot project did not proceed as planned, hence it is recommended that future evaluations on pilot projects should be carried out to strengthen the findings.

Overall, it can be concluded from evaluations that the designed artefact (VisiLean) was mostly successful in achieving original research objectives, and the evaluation process itself was suitable for the type of research it supported. The overall aim of the research that integration of product and process views could improve the production process was demonstrated.

7.2 Contribution to knowledge

The most important contribution to knowledge in this research is the newly designed artefact itself, i.e. VisiLean. VisiLean as a system embodies the knowledge that was generated through this research and helps overcome a practical problem identified during the early stage of the research. The VisiLean

system successfully demonstrated that the integration of process and product visualisation is beneficial to the production management process in construction. And also that a lean production management system built on such a visual foundation is perceived to be beneficial by the production teams on site. This particular aspect of a construction management system specifically designed for the use of construction project itself (during execution) was also perceived as a novel and useful concept during evaluations.

On a broader level, the research makes contributions to the theory of production. Koskela (2000) put forward the TFCV theory of production and argued that the dominance of transformation view in production has resulted in highly unstable and inefficient systems. Much has since been discussed regarding the application of TFCV theory in production and the overall construction process including design. The ramifications of the “T” view have been one strand of that discussion. However, they are not only limited to the production/construction management aspects, but their effects on other aspects such as information systems have been relatively neglected. The predominance of transformation view has led to silo type organisations, deep work breakdown structures, individual optimisation of processes (as opposed to the holistic view) and a general neglect of the flow and value aspects in production. Importantly, it also has had negative impacts on the information systems applied/implemented within the construction industry, which emerged as a separate finding during this research. Over the years, the information systems have been developed to support construction processes, which were controlled or designed from transformation viewpoint. As a result their effectiveness has been less than satisfactory, and in certain cases counterproductive as discussed in Chapter 3. Similarly there have been negative impacts on people (organisational) issues, and Table 6 shows the effects of TFCV on people, process and technologies.

This research demonstrates that not only it is important to satisfy TFCV goals while designing production management system, but it is equally important that the information systems that support the production management systems also support these goals. It was also recognised that in order to design an efficient information system, all three TFCV goals should be realised. Consequently, Table

19 in Chapter 5 outlined how VisiLean features address TFV requirements. From this perspective, it can be considered that this research makes direct contribution to the TFV theory within the context of information systems, as it identifies the effects of TFV on information systems design and implementation in construction, and more importantly addresses the TFV goals through VisiLean as demonstrated in Table 33.

Table 33. VisiLean's Contribution to TFV Theory.

VisiLean Feature	Transformation	Flow	Value
Process visualisation	Directly supports the production management process by providing suitable interfaces for the Last Planners.	Ensures minimal wastage during production by eliminating process clashes. Supports flow activities by providing a constraints management interface, and also by highlighting process clashes during execution.	Costs can be predicted and controlled better. Also reduced waste leads to reduced costs, which can be invested in value adding features (this is not same as value engineering, where the focus is on cost reduction).
Product visualisation	Provides the construction team a direct visualisation of “what” is to be constructed and “where”, directly supporting the transformation goals.	By providing the visual workflow of the tasks in hand, through simulation of phase, look-ahead, or weekly plan the system supports the flow activities in an efficient way	Through better visualisation of the design intent and what the client originally intended improves the value to the client
Product and Process integration	Improves the understanding of what is to be constructed, where and when.	Through integration of constraints analysis and status in production visualisation, improves the flow visualisation.	Reduces process waste (waiting time, variability and rework) ultimately improves quality and value.

In addition to the contribution to TFV theory as outlined above, the VisiLean research has provided a potential framework to improve three key aspects of the production management system in construction, namely Visualisation, Integration and Synchronisation. A discussion on each of these is provided next.

Visualisation. Tezel (2010) outlined the importance and effectiveness of visual information in a production management system. The VisiLean framework provides simultaneous visualisation of product and process views of production. This particular aspect has proved to be the most beneficial during evaluations and it emerges that it should be one of the core features of any future production management system implementation. Production planning, scheduling and control should not be carried out in isolation but rather be visually integrated with the product model. Particularly the visual aspects such as colour synchronisation of tasks (in the planning view) and BIM elements (in the model view) based on the current production status; visual flagging of resource conflicts and visual Pop-Ups displaying production related information on BIM element could be singled out as the most important contributions. The production status visualisation can be likened with visual “Andon” where the workers can flag upcoming and current problems by pressing an appropriate button in the system. Similarly, the task completion and readiness visualisations can be likened with KanBan implementation, supporting the “pulling” of work, rather than the “push” in the traditional system.

Integration. Integration in VisiLean is two fold, integration of production related information in a single platform and integration of product and process information (through lean and BIM systems), where both these aspects are equally important. Through the implementation of resource management in form of constraints and tracking of constraint status (i.e. the availability of a required resource on site), the VisiLean system integrates several information flows that typically have been managed manually on site (through traditional communication methods).

Synchronisation. Synchronisation also refers to two distinct yet connected aspects in VisiLean, namely synchronisation of up-to-date product and process views, and synchronisation of production status with both process and product views. As both parts of the system, the production planning and control workflow and the BIM model, are kept updated on a continual basis, they always reflect the up-to-date information leading to much better accuracy in planning and execution.

In summary, it can be emphasized that although the separate implementation of these aspects is not unique, the presence of all three aspects in a single system is unique and innovative and is also one of the main contributions of VisiLean research.

There are several other factors to consider while assessing the contributions to knowledge and theory, and as the VisiLean development is in a nascent stage and only one pilot project has been conducted so far, there is a potential for additional contributions to emerge.

7.3 Limitations of research

In Section 6.4, the critical evaluation of the current VisiLean prototype has been provided against a framework. Some shortcomings of the system have been identified from a point of view of completeness, usability, reliability, etc. Additionally, it emerges that the evaluation process itself had limitations, as the pilot project could not be completed as planned.

One of the main root causes behind the limitations of the research was of available time and resources, due to which only one pilot study of limited scope could be carried out. As a result, the evaluation and further refinement of VisiLean as a whole could only be carried out to a certain extent as reported. However, this was partly compensated by continuous evaluations carried out through demonstrations during meetings and workshops.

Similarly, due to the above-mentioned limitations, only one solution candidate could be developed. If these constraints were not present, possibility of developing several solution candidates to demonstrate different user interface designs, distinct process-product integration characteristics and utilisation of different platforms such as mobile and web could be undertaken.

Finally, as VisiLean was developed as part of a research project, it could not go through a rigorous testing process as commercial software systems, and hence can only be considered a prototype system that is not yet suitable for industrial deployment.

7.4 Future research

A number of topics emerged during this research, which could not be considered due the limitations of scope, and are proposed as topics for future research.

7.4.1. VisiLean in Design

One important aspect that emerged was the application of VisiLean during the design stage. Several participants highlighted that they have started to consider design as production, and are applying the Last Planner™ method of production planning to the design process. These organisations expressed the desire to test VisiLean during the design stage. Future research could focus on development of a framework based on which a system such as VisiLean could be extended to support the design stage, and bridge the gaps between the design and construction phases, resulting in efficiency improvements.

7.4.2 VisiLean in the Field

As highlighted in Chapter 5, use of VisiLean in the field emerged as an important feature for most participants, especially participants belonging to construction organisations. Production happens in the field, and if VisiLean as a production system can be extended on mobile platforms such as Smart Phones and tablets computers, it could make the production even more efficient, was the predominant view expressed by participants. Specific features related to the field application aspect of VisiLean can be found in Chapter 5. In future, dedicated mobile applications or web based universal applications (such as in HTML5) could be designed to support field application.

7.4.3 Other Features

Several other features such as cost and quantity integration at the task level, integration of the quality and safety workflow and support of collaborative knowledge management can be recommended for future research.

7.4 Conclusions

The research was addressing a two-fold research problem, first to address the deficiencies within the production planning process and secondly to demonstrate that it is possible to achieve improve production management with efficient information systems.

It can be concluded that the research largely achieved the original objectives as originally set out. Through VisiLean it was demonstrated that it is possible to support the production planning and control process on construction sites by integrating product and process visualisation through lean construction and BIM. Also, it can be concluded that the design science method was appropriate for the chosen type of research and future research in the area of information science within the construction may refer to this process.

The main conclusions from problem analysis were that the production management systems, especially the traditional planning and control systems were predominantly based on the “T” view and led to inefficiencies. It also emerged that in general the information systems within the construction industry support the traditional “T” based processes, and hence are not very effective at improving the efficiency of the core construction process.

During the exploration of potential solutions, it emerged that the application of lean construction principles, tools and techniques can help improve the efficiency of the construction process, and techniques such as the Last Planner™ system can help improve the efficiencies of the production management system. This mainly addresses the process management aspect in production. Similarly, it emerged that Building Information Modelling addresses many shortcomings of the traditional product modelling technologies such as 2D and 3D CAD. It also emerged that there are significant synergies between lean construction and BIM and that their simultaneous implementation could address many problems faced by the production management and control systems in construction.

It can be concluded from the design, development and evaluation process that taking a highly iterative and incremental approach to developing a solution such as VisiLean is effective. An important aspect to consider is that although VisiLean is a technological solution, the people and process angle are equally if not more important, and that any software system design project should take into consideration these aspects throughout the design and development as opposed to only testing the final solution after the prototype has been developed.

In conclusion, VisiLean can be considered a software framework based on which further production management functions can be added and a robust and comprehensive solution for an integrated construction management could be designed. It should be considered as a beginning of the next generation of software systems for construction industry, which address all TFV goals of the production system.

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Appendices

Appendix A: Evaluation Demonstrations

VisiLean was evaluated through a number of demonstration sessions with experts from the construction industry. These sessions took place either in an interview setting, i.e. one-to-one discussion, or through workshops where a number of participants were present. The candidate took notes during these sessions, which were then transcribed. The details of these evaluations sessions are provided in this Appendix.

Key Questions and classification framework

The companies can be classified under the following:

1. Nature of the company
2. Size of the company
3. Location
4. Exposure to lean philosophy and adoption on projects
5. Exposure to BIM on projects

Key questions asked

1. Relevance of research
2. Timeliness of research
3. Usefulness of research
4. Should the research be advanced to further stages (asked at the early stage of research)
5. Key features that you feel are important
6. Key aspects that need modification
7. What is missing? (i.e. any features you would like added)
8. Would you consider implementing it were it available?
9. Readiness for a pilot?
10. General comments
 - a. UI related comments (usefulness for people its intended for – i.e. site teams)
11. Do you think this is technologically viable –
 - a. i.e. communication infrastructure
 - b. software and hardware technologies

A.1 Interview Notes

Interview 1.

Nature/type	Construction (multiple)
Company Size	Revenue £11,035m (2011)
Location	International, UK
Exposure to Lean (proximity)	Yes, since 2004
Exposure to BIM	Yes.
Date of meeting	30/06/2010

Feedback from interview 1.

	Question	Feedback
1	Relevance of research	As the company has been trying to implement lean on projects, and also BIM is a current topic, the research is relevant and timely.
2	Timeliness of research	Yes, see above.
3	Usefulness of research	Currently, the lean workflow is achieved through manual post-it notes and Excel spread-sheets. There is a need for an integrated system that also allows constraints analysis and audit trail. As a concept it is very useful.
4	Should the research be advanced to further stages (asked at the early stage of research)	Yes, more features regarding integration of information sources (automated updating, importing data from other systems, and deeper integration with BIM) are desired.
5	Key features that you feel are important	Support of the collaborative planning workflow, integration with spatial (BIM) model.
6	What needs modification?	
7	Any features missing?	Addition of quantity and cost would make it more complete.
8	Similarities with other products	
9	Would you consider implementing it / readiness for a pilot	Would investigate possibilities of some live projects where this could be implemented.
10	General comments	Have been trying to find a solution for lean workflow for some time. Developed an excel spread-sheet linked to the

		programme to partially achieve this. However, this provides a much better platform for production planning as well as visualisation.
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Interview 2.

Nature/type	Construction
Location	UK (multi-national)
Exposure to Lean	Yes
Exposure to BIM	Yes.
Date of meeting	November 2010

Feedback from interview 2.

	Question	Feedback
1	Relevance of research	On many major projects, lean construction is being implemented. Especially where the client asks (i.e. in case of the Highways Agency). BIM is also finding its way in on most major projects. So this research is quite relevant.
2	Timeliness of research	Very timely as both lean and BIM are being demanded by clients.
3	Usefulness of research	See above.
4	Should the research be advanced to further stages	In general yes. However, it would be beneficial if the system supported integration with the planning system, distributed management of resources (i.e. constraints management).
5	Key features that you feel are important	Support of the collaborative planning workflow, integration with spatial (BIM) model.
6	Any features missing?	Addition of quantity and cost would make it more complete.
7	Would you consider implementing it / readiness for a pilot	Would investigate possibilities of some live projects where this could be implemented.
8	General comments	Have been using a number of systems to manage projects, including Primavera P6 for Planning and Autodesk Navisworks for visualisation. However, for Lean workflow, currently using a manual/traditional workflow. With the

		client demanding Lean it would be nice to have a system to manage it. However, it would be important to manage access control, and have a distributed system rather than a stand alone system.
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Interview 3.

Nature/type	Construction
Location	International, Finland
Exposure to Lean	Yes
Exposure to BIM	Yes.
Date of meeting	15 June 2011

Feedback from Interview 3.

Context: Meeting at project site for the company's new Headquarter building at Helsinki. Lean and BIM are being implemented at this project. Various tools and techniques are being applied including BIM use during collaborative lean planning sessions. Several BIM tools such as Tekla, Solibri and Vico are being used on site.

	Question	Feedback
1	Relevance, timeliness and usefulness of research	The company is implementing lean construction principles along with location based scheduling on almost all projects. BIM is also being used on all major projects. Particularly on the headquarter project, both lean and BIM are being applied simultaneously. The team feels that the research is highly relevant and timely to the needs of the industry. Currently Excel spread sheets are being used to facilitate the lean construction workflow (look ahead and weekly plans produced during last sessions are present on the site office walls). These spread sheets are not linked with any other system and hence makes the process more time consuming. Also, there is a dedicated BIM engineer who has to manually facilitate the navigation of model to demonstrate the current operating plan as the current tools being used on the site

		do not facilitate look-ahead or weekly level planning.
4	Should the research be advanced to further stages	Yes, and potentially collaboration with commercial solution providers will help proliferate such features in upcoming generations of respective BIM products.
5	Key features that you feel are important	Support of the collaborative planning workflow, integration with spatial (BIM) model.
6	What needs modification?	It is difficult to judge without testing the system thoroughly on a pilot.
7	Any features missing?	Addition of locations on tasks is especially desired. For example, most projects are divided in several locations, and tasks are then marked with these to enhance spatial awareness.
9	Would you consider implementing it / readiness for a pilot	Yes, would definitely be interested in organising a pilot

Interview 4.

Nature/type	Construction
Location	International, Finland
Exposure to Lean	Yes
Exposure to BIM	Yes.
Date of meeting	15 June 2011

Feedback from interview 4.

	Question	Feedback
1	Relevance, timeliness and usefulness of research	Currently the organisation is actively engaging in learning the implications of BIM within their internal processes. One of the BIM managers is currently in California with a Finnish delegation that is visiting some leading construction organisations learning about innovative use of BIM especially from IPD perspective. Hence, the research comes across as relevant, timely and useful.
2	Should the research be advanced to further stages	See above.
3	Key features that you feel are	The integration of lean construction aspects

	important	with BIM, and visualisation of planning activities are two most important features.
6	What needs modification?	Would like to see quantity linked with Tasks in the system, and if possible costs.
7	Any features missing?	
9	Would you consider implementing it / readiness for a pilot	Very keen on testing on a pilot project. Discussion to implement an on going project in Oulu.
10	General comments	Would be very keen to hear more on the future research in this area.

Interview 5.

2	Nature/type	Construction
4	Location	UK
5	Exposure to Lean	Yes
6	Exposure to BIM	Yes.
7	Date of meeting	July 2011

Feedback from interview 5.

	Question	Feedback
1	Relevance, timeliness and usefulness of research	The company has recently started implementing lean construction principles due to the demands from a major infrastructure client. The first two pilot projects are completed, where collaborative planning techniques were implemented. The company also implemented BIM on second pilot project. As the company faced several challenges due to the shortcomings of existing software systems, the research was found to be relevant, useful and timely.
2	Should the research be advanced to further stages	Positive response was received, with keen interest in collaborating, as one of the major client organisation is recommending the use of collaborative planning and BIM on all major projects.
5	Key features that you feel are important	In general, having an integrated platform will save duplication in efforts. On a motorway construction project the company had to maintain five separate spread sheets/databases to manage the collaborative planning process.

6	What needs modification?	Difficult to say without actually testing the system.
7	Any features missing?	Advanced reporting features including a dashboard where client can also access the progress of the project will be very desirable.
9	Would you consider implementing it / readiness for a pilot	Yes, would definitely be interested in organising a pilot. One of the project which starts in 2013 and is closer to the University could be suitable, as both Lean Construction and BIM will be implemented on this project.

A.2 Workshops Notes

Workshop 1 – SCRI Steering Committee

1	Location	Manchester, UK
2	Type of organisations represented	Academic, research, construction
3	Purpose	Demonstration
4	Date of workshop	15 December 2010

Feedback from workshop 1

- In general the feedback was positive. Many participants highlighted the importance of including cost and quantity information along with planning to improve the system's applicability
- It was also indicated by participants of the workshop that the system seems to be commercially viable and relevant companies should be approached to pursue collaboration.
- One of the participants who had contacts with a particular client organisation asked if the research team would be interested in organising a trial on an upcoming construction project of a prison.
- It was highlighted by a participant that such a system would only be useful if the designers hand over a sufficiently detailed model with a proper element hierarchy.

Workshop 2 – SCRI Forum

1	Location	Manchester, UK
2	Type of organisations represented	Academic, research, construction, Design
3	Purpose	BIM for Contractors
4	Date of workshop	13 March 2011

Feedback from Workshop 2

- A participant asked if the system can be integrated/synchronised with other planning and construction information systems such as Primavera P6 or Asta Teamplan.
- Many participants mentioned that it looks like a product, and asked if it is available to try or buy.
- A question was asked whether it supports the Industry Foundation Classes.
- The need to help automate the reports such as A3, reasons for non-completion etc. were highlighted.

Workshop 3 – Ratu, Finland

1	Location	Helsinki, Finland
2	Type of organisations represented	Academic, research, construction, Design
3	Purpose	Productivity group workshop, demonstration of research
4	Date of workshop	16 June 2011

Feedback from Workshop 3

- One of the participants, already applying lean construction and BIM on their projects highlighted the importance of adding locations to tasks. It was mentioned that their common practice is to divide the site in several locations (if it is not naturally divided in levels), to help identify where the tasks are located. This helps construction workers during planning and execution.
- Several participants highlighted that they currently do not use lean or BIM so the system does not come across as relevant to them.

- In general positive feedback was received, with follow up enquiries to trial the system on future projects.

Workshop 4 – A Major Nuclear Energy Organisation

1	Location of workshop	UoS, Manchester, UK
2	Type of organisations represented	Client, Contractors, Design
3	Purpose	Demonstration of research
4	Date of workshop	06 June 2011

Feedback from Workshop 4

- As the workshop being organised for a large client organisation, who maintain a very large asset (facility), there was an increased interest from the perspective of using the system post construction. It was highlighted that although the system is not being designed from that perspective, it has a potential to be used during facilities maintenance.
- One of the users suggested that the future development should include features such as augmented reality to help locate hidden objects/services during facilities maintenance.
- Linking of other rich media such as videos and photos to support activities such as snagging was suggested, along with integration with quality and safety management system.
- Integration with other information management systems such as Knowledge Management and Document Management was suggested.

Workshop 5: A Large Construction Company

1	Nature/type	Construction
2	Location of workshop	UoS, Manchester, UK
3	Exposure to Lean	Little
4	Exposure to BIM	Yes.
5	Date of meeting	14 th October 2011
6	Present in workshop	Group BIM Manager, Project Managers, Procurement Manager, Quantity Surveyors, Site Supervisor, Group IT Manager

Feedback from Workshop 5

The workshop was a part of a series of six workshops to help formulate the company's BIM strategy. The workshop involved participants from various backgrounds, i.e. site managers, project managers, BIM managers and process improvement specialists. The participants provided feedback following a VisiLean demonstration:

- It was suggested that it should be made possible to link cost and quantity information to the system.
- It was felt that this is the future of the production control on site
- Questions were asked whether this would apply to on-going projects
- When asked a specific question following the presentation about whether the company will consider implementing a 4D production management system the following answer was given: "Had you asked the question before the presentation, the answer could have been different, but now the answer is a definite yes"

Appendix B – Agile Programming Methods

B.1 Extreme Programming (XP)

Introduced by Beck and Jeffries (Beck, 1999a), XP is based the values of simplicity, communication, feedback and courage. In Table 1, 12 rules of XP are described, which provide a simple and concise framework.

Table 1. Extreme Programming Framework

- | |
|--|
| <ul style="list-style-type: none">• The planning game: At the start of each iteration, customers, managers and developers meet to define, estimate and prioritise requirements for the next release. The requirements are called “user stories” and are captured on “story cards” in a language understood by all parties.• Small releases: An initial version of the system is put into production after the first few iterations. Subsequently, working versions are put into production anywhere from every day to few days to every few weeks.• Metaphor: Customers, managers and developers construct a metaphor, or a set of metaphors after which to model the system.• Simple design: developers are urged to keep design as simple as possible• Tests: Developers work test-first, that is they write acceptance tests for their code before they write the code itself. Customers write functional tests for each iteration and at the end of each iteration, all tests should be run.• Refactoring: As developers work, the design should be evolved to keep it as simple as possible• Pair programming: Two developers sitting at the same machine write all code• Continuous integration: Developers integrate new code into the system as often as possible. All functional tests must still pass after integration or the new code is discarded• Collective ownership: The code is owned by al developers, and they make changes anywhere in the code at anytime they feel necessary.• On-site customer: A customer works with the development team at all times to answer questions, perform acceptance tests, and ensure that development is progressing as expected• 40 hour weeks: Requirements should be selected for each iteration such that no overtime work is needed• Open workspace: Developers work in a common workspace set up with individual workstation around the periphery and common development machines in the centre. |
|--|

The consensus from the practitioners is emerging that the strength of Extreme Programming is in combination of the 12 principles listed above rather than their individual implementation. It is also recommended to keep the minimum iteration cycle as 2 weeks.

B.2 Scrum

Along with XP, Scrum is also one of the most popular Agile methods. It was described by Ken Schwaber in 1996 (Schwaber and Beedle, 2002) as a process that “accepts that the development process is unpredictable”, formalising the “do what it takes” mentality, and has been since applied by a large number of independent software developers.

The term Scrum is inspired from the sport rugby, where “Scrum occurs when players from each team huddle closely together in an attempt to advance down the playing field” (Highsmith, 2002). There are three key stages in a Scrum project:

- Pre-sprint planning: Here, all the work that needs to be done on the software development is allocated to a “release backlog”. During this meeting, features and functionalities are selected from the release backlog and placed into the “sprint backlog” to be prioritised for completion during the next spring. It also identifies the reasons behind the performance of tasks and at which level of detail they need to be implemented (Highsmith, 2002).
- Sprint: Once the pre-spring meeting is complete, the teams are allocated their spring backlog and asked to “spring to complete the backlog” (Schwaber, 2009). Here, the tasks in the Sprint backlog are frozen and remain so for the duration of the Sprint. The priorities are set by the team members themselves and short daily meetings are organised to discuss progress.
- Post-sprint meeting: A post-Sprint meeting is organised to discuss and analyse the progress and any obstacles, and also to demonstrate the current system.

The key principles of Scrum can be summarised as (Schwaber, 2009):

- Small working teams that maximise communication, minimise overhead, and maximise sharing of tacit, informal knowledge
- Adaptability to technical or marketplace (user/customer) changes to ensure the best possible product is produced

- Frequent “builds”, or construction of executable, that can be inspected, adjusted, tested, documented and built on
- Partitioning of work and team assignments into clean, low coupling partitions, or packets
- Constant testing and documentation of a product as it is built
- Ability to declare a product ‘done’ whenever required (due to the reasons related to competition, cash flow, user/customer need, or deadline).

B.3 Crystal Methods and Feature Driven Development

There are many other methods such as the Crystal Methods which were developed to address the poor communication during the product development stage in early 1990s and the Feature Driven Development method which was developed in the late 1990s (Paetsch et al., 2003). The Feature Driven system emphasises on defining a simple process and producing immediate output at each step that has value to all stakeholders. Similar to Scrum and Extreme Programming, both these methods also emphasise on the iterative and incremental cycle along with placing emphasis on collaboration.

Key features for the Crystal Methods are (Paetsch et al., 2003):

- Incremental time-boxed delivery (Prototyping, Reviews)
- Automated regression testing of functionalities (Testing)
- Two user viewing per release (Review)
- Workshops for product and methodology-tuning at the beginning and in the middle of each increment (Review)

Highsmith (2002) describe the core values of Feature Driven Development as:

- A system for building systems is necessary in order to scale to larger projects
- A simple, well-defined process works best
- Process steps should be logical and their worth immediately obvious to each team member
- “Process Pride” can keep the real work from happening

- Good processes move to the background so the team members can focus on results
- Short, iterative, feature-driven life cycles are best

B.4 Dynamic Systems Development Method (DSDM)

DSDM is a framework that is a formalisation of Rapid Application Development practices (Highsmith, 2002). The DSDM lifecycle has six stages:

- Pre-project: The pre-project phase indicates the readiness of the project, its finance and other resources needed to initiate and carry out the project.
- Feasibility study: In DSDM it is stressed that the feasibility study stage should be short (preferably a few weeks), and help determine the right approach for the project.
- Business study: The main aim of this phase is to leverage the knowledge from relevant team members, and organise facilitated workshops. It is a highly collaborative phase, where the end result is a definition of the business area, which identifies key users of the system, markets, and the business processes affected by the system.
- Functional model iteration: One of the key early stages during system design, during functional model iteration a number of prototypes are developed using the high level requirements defined in previous stages. This phase and the subsequent phase of design and build iteration share a common process:
 - Identify why is to be produced
 - Agree how and when to do it
 - Create the new product
 - Check that it has been produced correctly (by reviewing documents, demonstrating a prototype or testing part of the system)
- Design and build iteration: In this phase, the prototypes developed in the previous phases are fully developed, and tested to deliver a working system to the users

- Implementation: In this phase the system is implemented and put into use. A review is carried out to identify whether the system meets user requirements, and if there is any additional work to be done. The previous stages are iterated if any additional work is to be carried out.
- Post-project: During this phase, on-going maintenance and updates to the system are carried out.

There could be a number of variations of these methods and other lesser known methods in use to facilitate system development.

Cohen et al. (2003) compare selected agile methods and highlight key difference. The authors highlight that the Scrum method of agile development is suitable for use in small teams (1-7), and has a relatively quicker iteration cycle, where outputs can be inspected, and adjusted.

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Paetsch, F., Eberlein, A., & Maurer, F. (2003). Requirements engineering and agile software development. In *Enabling Technologies: Infrastructure for Collaborative Enterprises, 2003. WET ICE 2003. Proceedings. Twelfth IEEE International Workshops on* (pp. 308-313). IEEE.

Schwaber, K. (2009). *Agile project management with Scrum*. Microsoft Press.

Schwaber, K., & Beedle, M. (2002). *Agile software development with Scrum* (Vol. 18). PTR Upper Saddle River NJ: Prentice Hall

Appendix C Additional VisiLean Images

This appendix provides high resolution screen shots of VisiLean prototype describing various functions of system for improved clarity.

Figure 1 shows the phase planning screen shot with approximately three months duration of tasks shown. One key feature is visualization of different task statuses from production planning and control perspective. For example, the image shows the “prepare grading” task that is not ready as the resource allocated to it, “JCB Backhoe”, is not available yet. Resource constraints can be added either in the Phase or Lookahead planning stage.

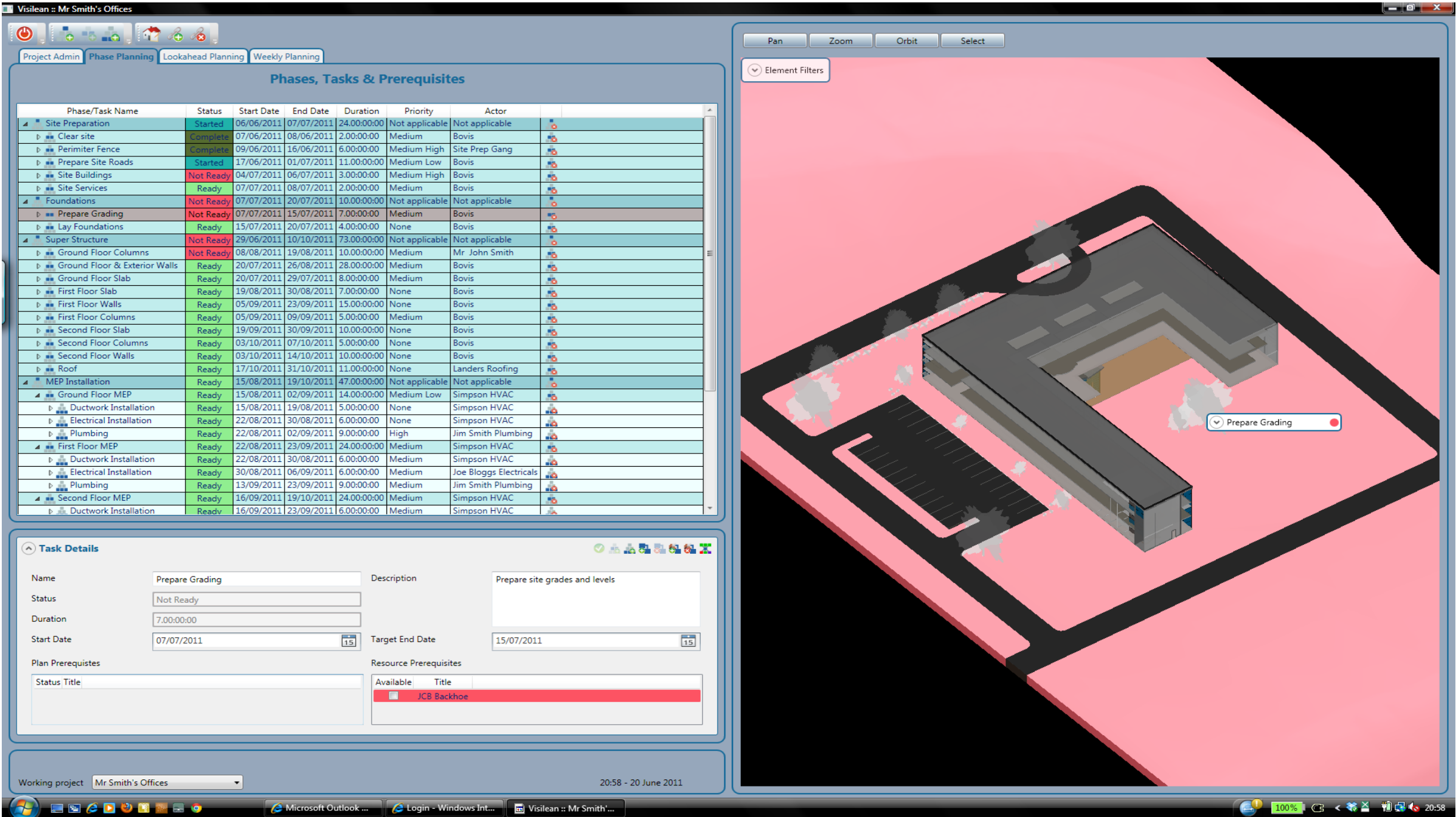


Figure 1. Phase Planning in VisiLean.

Figure 2 shows tasks within a two week Lookahead planning window. The main goal is that once these tasks are selected in the Lookahead plan, both the teams (Team A and Team B) will list all the constraints associated with each of the tasks. Within the next two weeks they will have the opportunity to remove the constraints and get the tasks ready for the weekly execution work plan. Only those tasks with “ready” status can then be released to the weekly plan.

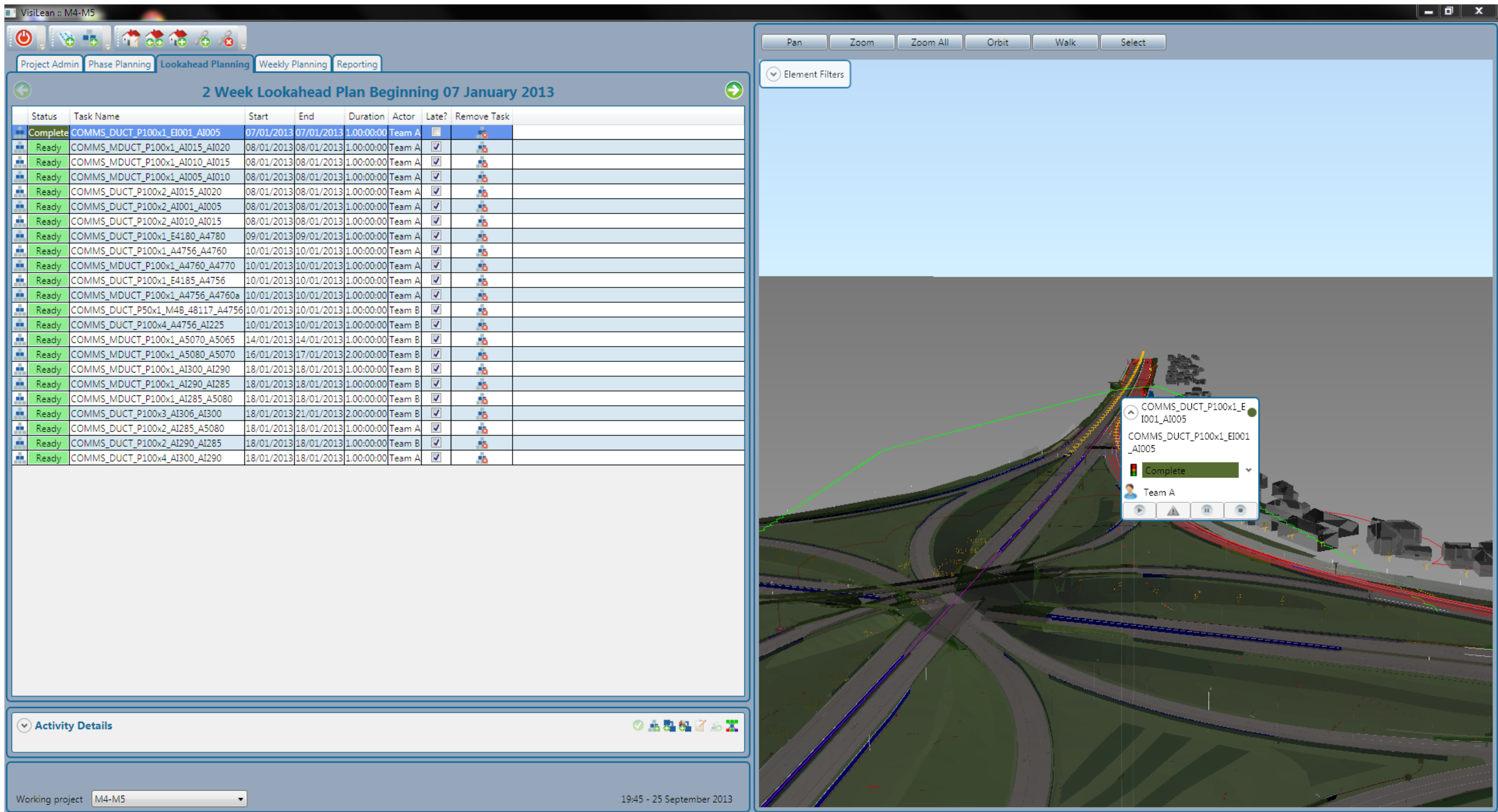


Figure 2. Lookahead planning screen, showing tasks within a two week window.

Figure 3 shows the weekly work plan where the selected task is ready as the single constraint that is associated with it is marked as available. Also note that the task pop-up in the model view shows a green “ready” symbol against the element in the model. During the execution week, the teams will use the start, stop and complete buttons to indicate the current status of the task.

The screenshot displays the VisiLean M4-M5 software interface, which is divided into several panels. The top panel shows the 'Weekly Work Plan Beginning 07 January 2013' with a summary: Total Tasks 14, Completed Tasks 1, and Percentage Plan Complete 7.14. Below this is a table of tasks.

Status	Task Name	Start	End	Duration	Actor	Late?	Remove Task
Complete	COMMS_DUCT_P100x1_EI001_AI005	07/01/2013	07/01/2013	1:00:00:00	Team A		
Ready	COMMS_MDUCT_P100x1_AI015_AI020	08/01/2013	08/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_MDUCT_P100x1_AI010_AI015	08/01/2013	08/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_MDUCT_P100x1_AI005_AI010	08/01/2013	08/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x2_AI015_AI020	08/01/2013	08/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x2_AI001_AI005	08/01/2013	08/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x2_AI010_AI015	08/01/2013	08/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x1_E4180_A4780	09/01/2013	09/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x1_A4756_A4760	10/01/2013	10/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_MDUCT_P100x1_A4760_A4770	10/01/2013	10/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x1_E4185_A4756	10/01/2013	10/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_MDUCT_P100x1_A4756_A4760a	10/01/2013	10/01/2013	1:00:00:00	Team A	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P50x1_M48_48117_A4756	10/01/2013	10/01/2013	1:00:00:00	Team B	<input checked="" type="checkbox"/>	
Ready	COMMS_DUCT_P100x4_A4756_AI225	10/01/2013	10/01/2013	1:00:00:00	Team B	<input checked="" type="checkbox"/>	

The bottom-left panel shows 'Activity Details' for the selected task 'COMMS_MDUCT_P100x1_AI015_AI020'. The status is 'Ready'. The duration is '1:00:00:00'. The start date is '08/01/2013' and the target end date is '08/01/2013'. The responsible actor is 'Team A'. The constraints section shows a conflict with 'Comms Installation Instrument', which is marked as 'Satisfied'.

The right panel shows a 3D model view of the project. A pop-up window for the selected task 'COMMS_MDUCT_P100x1_AI015_AI020' is visible, showing a green 'ready' symbol. The 'Element Filters' panel on the left lists various elements, including 'COMMSROUTE' and 'COMMS_DUCT_P100x1_AI015_AI020'.

Figure 3. Screen shot showing a weekly work plan.

Figure 4 shows the task filtering during planning to facilitate selection of tasks based on various criteria such as organisation, role, space, status and date, etc. Filtering will be used during the collaborative planning meetings to visualise a selection of tasks, which can then be reviewed and appropriate action taken.

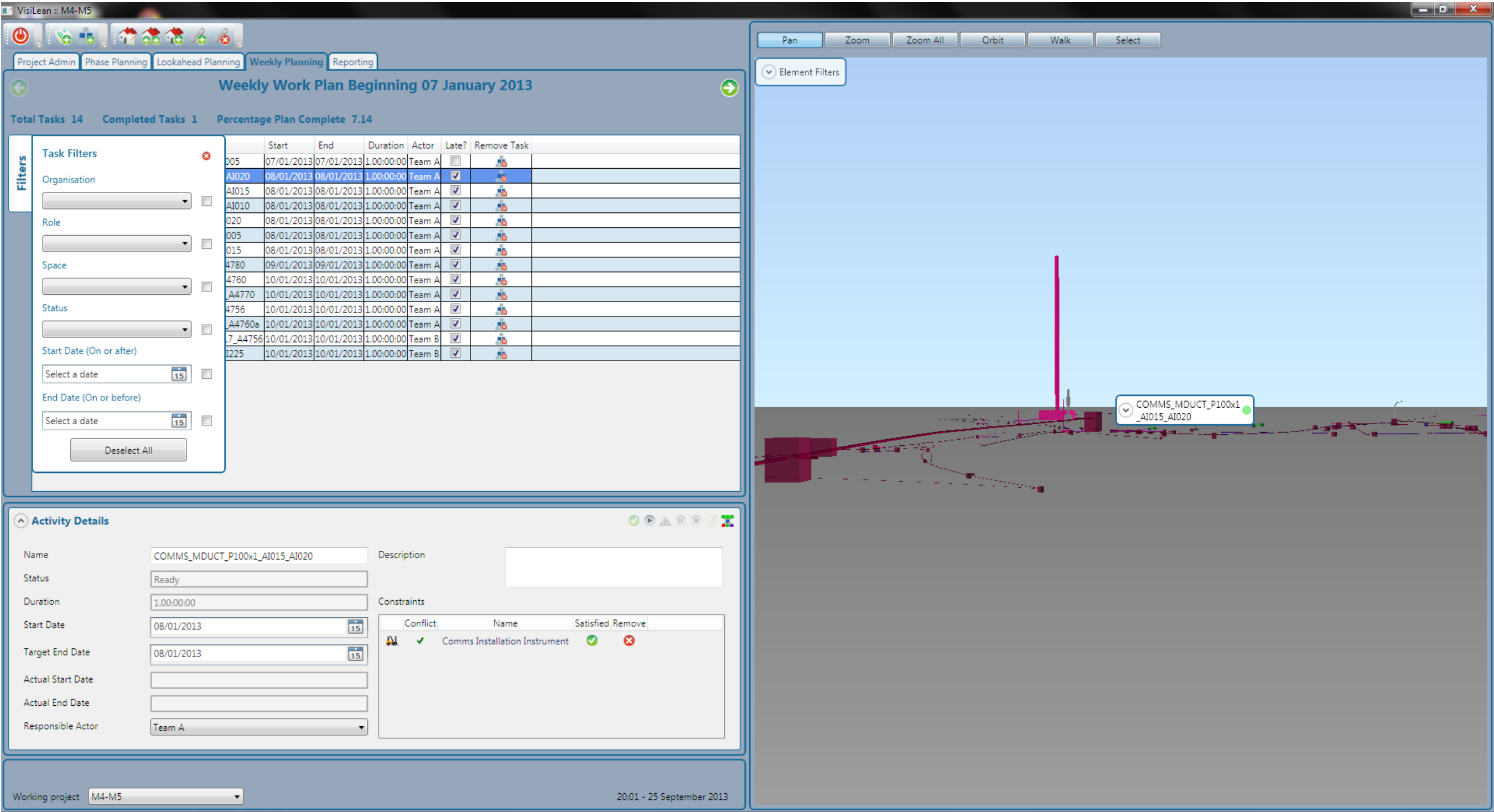


Figure 4. Task filtering during planning in VisiLean.

Figure 5 shows the top-level system architecture and is a high resolution version of Figure 39, which was shown in Chapter 5.

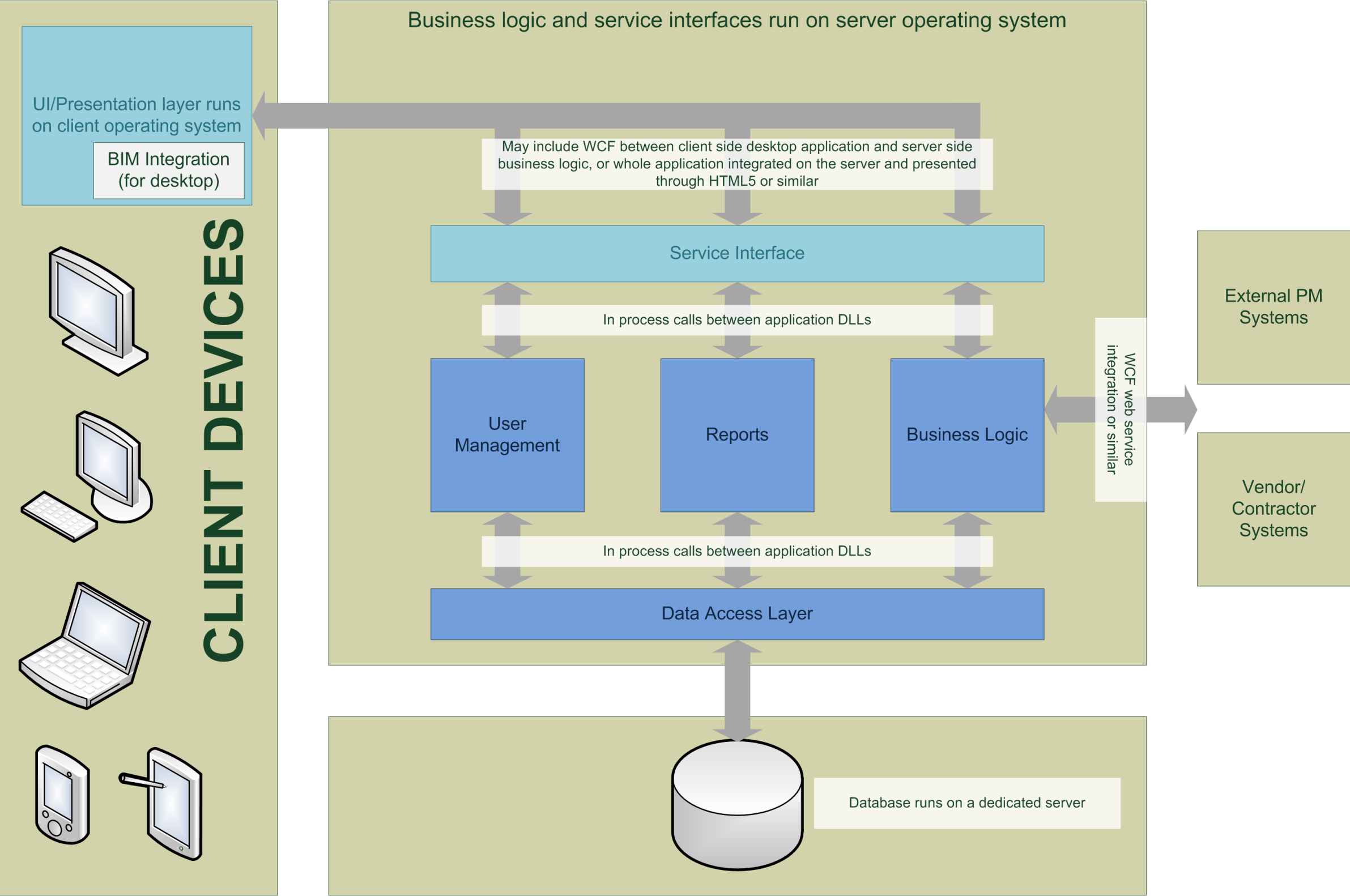


Figure 5 - VisiLean System Architecture (high resolution)