2021

To What Extent Can Lean Construction Processes and Principles be Utilised in the Design Stage of a BIM Project in the Irish Design and Construction Industry

BIM TUDublin
bim@tudublin.ie

Barry Sheramn
Technological University Dublin

To What Extent Can Lean Construction Processes and Principles be Utilised in the Design Stage of a BIM Project in the Irish Design and Construction Industry

Barry Shearman[1] and Barry Kirwan[2]

School of Multidisciplinary Technologies,

Technological University Dublin, Ireland.

E-mail: [1]C14329586@mytudublin.ie [2]barry.kirwan@tudublin.ie

Abstract – Although different in many ways, Building Information Modelling (BIM) and Lean Construction are two processes that are having a significant impact on the Design & Construction Industry. In recent years, the Irish AECO industry has seen a ten-fold increase across numerous construction disciplines with the adoption of new workflows and processes centred around both BIM and Lean methodologies. Existing literature identifies a strong synergistic relationship between the two processes and highlights the opportunity for Lean processes and principles to be implemented into the design stage workflow. This paper investigated existing literature relating to several lean processes currently implemented in the construction industry and specifically highlights Target Value Delivery (TVD), Last Planner System (LPS) & Set Based Design (SBD) as suitable for implementation during the design stages. The Thematic Analysis method was used for analysing the datasets obtained from the online questionnaire and interviews to help gauge industry awareness and opinion relating to the implementation and potential constraints associated with the side-by-side implementation of these processes. An interaction matrix that investigated the positive and negative interactions associated with the synergistic relationship between the two processes was carried out as part of this research. Additionally, this paper investigated and collated a list of barriers that exist in today's design and construction industry that continue to prevent a complete and successful BIM project delivery process and specifically highlighted the need to identify the value to project stakeholders when implementing these new processes throughout all project areas of the AECO industry.

Keywords – Building Information Modelling (BIM), Lean Construction, Target Value Delivery (TVD), Last Planner System (LPS), Set Based Design (SBD), Identifying Value.

I Introduction

Traditionally, there has been a clear and defined line between design and construction teams in the industry with the design team typically led by the Architect, also acting as the client's representative and the construction team led by the main contractor. Theoretically, both teams involved in the project are working towards the same goal of design, constructing and managing an asset. Having said that, the culture that exists throughout the industry is inefficient and often lacks collaboration amongst stakeholders. Unsurprisingly, this culture can lead to great inefficiencies, with added costs, overrun of programmes and usually a disconnect between project teams. Although the traditional procurement method is the most common method, in more recent times the use of more collaborative procurement methods have been implemented on more projects, for example Integrated Project Delivery (IPD) [1] which is based on a shared risk and reward method for each stakeholder involved in the project [2]. Throughout the past decade and still today new technologies and processes are being implemented into the construction industry. These new ways of working have allowed industry professionals to understand, plan, design, construct and manage more efficient and smart buildings. The main process to emerge in the construction industry from the technology revolution is the Building Information Modelling (BIM) process. BIM acts as an enabler for collaborative environments within project teams with research in this area often linked to lean thinking [3], [4], [5]. In recent years, many organisations in the construction industry have changed their own processes and workflows inhouse by adopting lean thinking methods / processes that were first used in the manufacturing industry [6], [7], [8]. Existing research within the area of BIM & Lean tends to focus on construction firms and the construction stage of the delivery process. Alternatively, fewer papers investigating the application of these processes in the design stages have stated that lean processes are also effective for planning and controlling other project stages such as the design stage [9].

The design stage of any construction project has a significant contribution to the quality and outcome of the overall project performance with immediate influences on the construction stage and further influences during the operational phase of the built asset [10]. Poor outcomes in the design stage or improper design have a knock-on effect that largely contribute to project delays, rework, budget overrun and overall poor performance and quality. As design itself is an iterative process [11], this can often lead to many changes as the design develops. The design stage is the cheapest stage to capture these changes and can save a substantial amount of money for the client as during construction the cost to the client will be far greater. Ko & Chung [12] define improper design as a design error that is caused by design itself and incurs a change order in the construction stage which is viewed as one of the biggest sources of waste [12]. Freire & Alarcon [13] state that the planning and control in design is substituted by chaos and improvising which causes lack of resource allocation, production of inadequate documentation, poor communication and the lack of coordination amongst the project team [13]. According to Tzortzopoulos & Formoso [14] the traditional design delivery process fails to minimise the complexity of design information and ensure that outstanding design information required during the construction stage needed to complete tasks is readily available in order to reduce the inconsistencies that occur in the production of construction information.

II Review of Literature

The literature reviewed for this paper provides the input for the first two objectives of this study and contributes to the development of the third and fourth objective. The first objective is to critically review the lean processes and principles currently implemented in the design and construction industry. Several Lean processes were investigated, including TAKT Time, Last Planner System (LPS), Target Value Delivery (TVD), Set Based Design (SBD), Kaizen, Six Sigma & 5S. By process of elimination based on a scoring matrix, the three best suited lean processes were investigated further.

The second objective considers literature relating to the BIM project delivery process for the design stage by investigating the potential barriers and synergy between lean principles / processes and the BIM process.

a) Origins of Lean

Lean is a core idea with the overall aim of maximising customer value while minimising waste by using less resources [15]. A common misconception is that lean is only suitable for the manufacturing and production industry. As a matter of fact, this is far from reality as the Lean Enterprise Institute [16] state that lean applies to all businesses and processes.

The first lean production model was developed by Toyota’s Chief of Engineering, Tachnii Ohno in 1930. From Ohno’s production model “The Toyota Way” Ohno [17] identified seven types of waste linked to traditional production methods. The seven types of waste are as follows; 1. Overproduction, 2. Waiting, 3. Transporting, 4. Over-Processing, 5. Inventories, 6. Moving, 7. Making defective parts and products. According to Ohno, the fundamental waste is overproduction as it causes most of the other wastes [17]. During the 1990’s after the Toyota Production System (TPS) was adopted by the western world and the non-utilisation of talent / skills of workers was identified as the eighth waste [18]. In addition to the identification of the seven wastes, 14 principles were also identified as part of “The Toyota Way”. The principles outline as a set of guidelines to provide the tools to allow the workers to continuously improve their work. The philosophy of the Toyota way means that there is more of a dependency on people rather than less, by depending on people to reduce inventory, identify hidden problems and to fix these problems. This causes a sense of urgency, purpose and teamwork in order to prevent inventory outage [19].

b) Lean in the Design & Construction Industry

Lean production processes and principles have been around the construction industry for quite some time and were first introduced during the 1990’s [19]. Lean construction is a process-based approach that applies lean thinking to the planning, design, construction, management and deconstruction of a built asset [15].

According to O’Neill [20], the construction industry in several countries have well established lean processes and principles in everyday workflows. Having said that a commonality that exists throughout many professionals throughout the industry is that there are still mixed views in terms of the interpretation, understanding and implementation of these methods [21]. In the Irish Design & Construction Industry lean is a relatively new concept. As O'Neill [20] states, from literature and industry communication, the concepts and their benefits investigated in many academic papers are often met with scepticism. Traditionally, the planning of the tasks required in the design stage have been organised from the top down by project managers and team leads meeting on a regular basis to identify upcoming tasks on a master schedule, without checking with the wider team if the tasks and the agreed timeframe is realistic to achieve [22].

Target Value Delivery (TVD) is defined as a disciplined management method implemented during the stages of a project to assure that the built asset meets the operational needs and values of the end user, is delivered within the allowable budget, and promotes innovative workflows throughout the project to increase value and eliminate waste. TVD was adapted from manufacturing's Lean Product Development. Target Value Design (TVD) encompasses the Target Value Delivery approach and is implemented during the design stages of a project [7]. Using TVD the design and construction is steered towards the target cost set at the beginning of the project. Traditionally, the cost management method used on projects determines the cost of the product based on its design and the estimated cost of realising the design. On the other hand the Target costing method is focused at the beginning of a project before the design has been carried out and the cost of the product (built asset) is determined before the design and is based on the client's requirements outlined in the business case [23]. In figure 1 below the value of the client's benefits outlined in the business case must be greater than the sum of the first four circles which account for the entire project costs including the operational stage of the asset for the project to proceed [7].

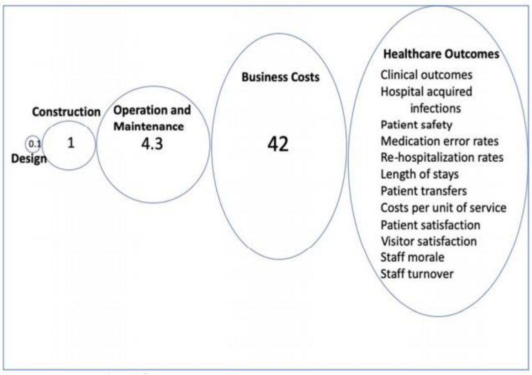

Figure 1 – Cost/Benefit ratio illustration [7]

In 2019 Ballard [24] carried out a case study on a Healthcare project in the United States that implemented the TVD process with the aim of identifying client value project requirements through the business case from project inception. Sutter Health's Fairfield Medical Office Building Project had an estimated cost of $22 million based on similar projects carried out in the past. At the beginning of the project using the Target Cost method in TVD, the target cost was set at $18.9 million based on the return of investment from the use of the building through its design life. Due to the reduction of cost for design and construction during the project as a result of a combination of factors which included integrating builders into the design team, quick feedback in relation to design alternatives and shared risk and reward for all project stakeholders the actual cost at project completion was $17.9 million which was a cost reduction of 5.2% below the target cost and 18.6% below the market [7].

Although Ballard [25] states that in order to maximise the benefits of implementing TVD on a project the most suitable procurement method is an Integrated Project Delivery (IPD) procurement. Ballard also stated that it is still possible to benefit from implementing TVD during the design stage of other projects that use a different procurement method to IPD.

The Last Planner System® (LPS) is defined by Rafael Sacks in Building Lean, Building BIM as a production planning and control method with the aim of stabilising the flow of work, making plans predictable and reliable, therefore minimising waste alongside adding value to the construction process and the customer. Designated project planners review work packages prior to releasing the packages to the relevant project teams to ensure that the preconditions of the work have been fulfilled [9]. The LPS is made up of five key sections; master planning, phase planning, look-ahead scheduling, weekly work planning and monitoring of outcomes which is usually monitored by using a "percent plan complete" (PPC) [9]. In the early stages of the project the first step is master planning, which defines the project at a high level and is intended as a framework for outlining the project milestones to determine if the project can be delivered to meet the requirements outlined by the client. The next stage phase planning, each major stage outlined in the master plan schedule is expanded into its component tasks. Phase planning recognises that 'over planning' at the beginning of the project in advance of the relevant stage is considered a waste. During phase planning the standards are set for the base of the detailed task schedule that will be developed by all project stakeholders at a later stage of the process. The main aim of the phase planning stage is to identify and organise specific tasks between different stakeholders to ensure a greater flow of work is achieved during each stage of the project. The look-ahead plan ensures that all prior tasks that affect upcoming project tasks have been completed to ensure that there are no constraints existing that may prevent the next set of tasks being carried out. Lastly, the plan of tasks for the upcoming week is developed in a "Weekly Work Planning" (WWP) meeting where each stakeholder involved in the project gives a project update and develops a plan for the upcoming week. This plan outlines each stakeholder's commitments to completing specific tasks. Unlike traditional planning, the plan is prepared by each discipline on the project team rather than one individual [9].

Multiple case studies carried out by Lean Construction Ireland [6], [7], [8], on Irish Construction firms and a number of international papers have identified the successful implementation of the LPS during the construction stage of projects [7], [6], [26], [27]. On the other hand, several papers [4], [22], [28], [27], [29], [30] have investigated the implementation of lean processes during the design stage of a project, with most highlighting the barriers present as opposed to a successful adoption. Some researchers report that the application of LPS during the design stages of projects have been limited in scope but the application of a modified LPS during the design stage is achievable [22]. Khan & Tzortzopoulos state that WWP as a pull planning tool has been used very effectively in the past on construction stages of projects, but its application to the design stage has not been widely investigated [22].

Typically, the traditional design method also known as point-based design is a linear process by nature, meaning a single design option is selected at the beginning of the project and further developed through each stage of design(reference). Alternatively, Set Based Design (SBD) is a design method developed by Toyota where the designer is developing multiple design options at the same time [31]. The SBD process starts with a wide range of possible solutions and as the design and client requirements develop the possible options are gradually narrowed down until the best suited option is selected at the last responsible moment [32]. Sobek et al. [31] outlined the three main principles of SBD. The first principle; Mapping the design space. This principle consists of defining the feasible regions, exploring the trade-offs by designing multiple alternatives and communicating the desired sets of possible solutions. The second principle; Integrating by intersection is identifying the possible intersections that occur throughout the range of sets that have been identified along with imposing the minimum constraint which allows for flexibility and the possibility of further exploration or adjustments to improve integration. The goal of this principle is to "*apply the minimum constraint necessary to achieve the performance levels, which leaves it up to the supplier to complete the details*". The third principle; Establishing feasibility before commitment involves exploring the multiple designs in a parallel nature and gradually converging on a single one. A key part of the set based process is the decision making process that gradually eliminates possibilities until the final solution remains [31].

As the application of SBD untimely relies on an effective decision-making method, the most robust method is Choosing by Advantages (CBA). Although the SBD process is a concurrent engineering process, a small number of research papers [11], [33], have investigated the possibility of adopting this process in the design and construction industry. According to Do [32] CBA and SBD has been used on a variety of lean construction projects in the past to make the design process more efficient. Do [32] also states that a number of advanced lean construction teams have implemented CBA, SBD in LPS.

Three common lean processes implemented in the construction industry as mentioned in detail above; 1. Target Value Delivery (TVD), 2. Last Planner System (LPS) and 3. Set Based Design (SBD). Although each of the three processes are different, the same core lean principles provide the foundation for each of the processes. Similar to the Lean Process literature review, the next section of this literature will review the existing literature relating to the current BIM Project Delivery Process with the aim of identifying differences and/or parallels between the two processes which will contribute to the positive & negative interaction matrix proposed at a later stage in this study.

c) BIM Project Delivery

Building Information Management (BIM) is a digital-based process of designing, constructing, managing and operating both graphical and non-graphical data of a built asset that is stored in a single source digital database or Common Data Environment (CDE) [34]. The benefits of adopting the BIM Project delivery process have been widely investigated and debated to-date, where it continues to be a hot topic around the industry. According to the 2025 Industrial Strategy for Construction set out by the United Kingdom (UK) Government, the implementation of BIM processes and technologies on construction projects will play a key role in the reduction of costs in the initial construction stage and the cost over the life-cycle of the built asset by 33%, reduce project delivery programmes of new and refurbished built assets by 50% and lower the carbon footprint of the industry by 50% [35].

The first step of the BIM process is to start with the end in mind. At the end of the information delivery stage of the project the appointing party or client will receive the Asset Information Model (AIM) which is developed throughout the different stages of the project by the project team. The Asset Information Requirements (AIR) which is an information document developed in the early stages by the Lead Appointed Party of the delivery team, specifies the AIM. Before the AIR are identified the OIR's need to be outlined by the appointing party as the OIR encapsulates the AIR. McArthur [36], highlights the importance of identifying the relevant and value-adding information required for the asset information model. However, McArthur also states that much of the information that is typically included in AIM is not necessary for day-to-day operations of the asset. As stated in ISO 19650 Part 1: 2018 [37] the OIR involves categorising and establishing the information requirements that meet the needs of the appointing parties asset management system. Figure 2 below outlines the hierarchy of information requirements and information models from ISO 19650-1:2018 that are present in the BIM project delivery process. Additionally, the OIR also provides an input into the Project Information Requirements (PIR) which are a set of questions required to be answered by the delivery team at each of the appointing party's key decision points.

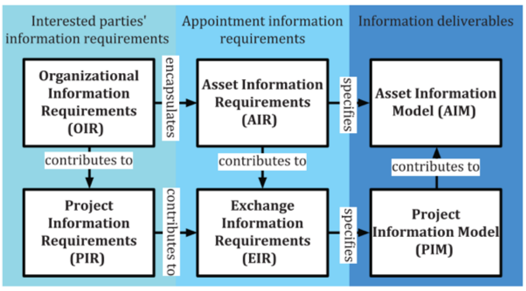

Figure 2 – Hireachy of Information Requirements [37]

According to the NBS National BIM Survey 2014 [38] there were a number of barriers identified with the BIM process and the implementation of BIM on projects with 73% of respondents stating that there is little or no demand for BIM on projects by clients, 71% of respondents felt that the BIM process was not feasible for small practices and projects and high costs linked to training employees in BIM processes and technologies due to the lack of existing knowledge were the key barriers. Six years on, the 10th NBS Annual BIM Report [39] published in 2020 contained a number of the same BIM implementation barriers as before. Although great strides have been made from many government bodies and professionals in the AECO industry several of the same barriers to BIM implementation still exist. Although 73% of respondents stated that they are using BIM, 62% of respondents in firms of less than 15 people have adopted BIM compared to 80% adoption from firms larger than 50 people with almost two thirds of respondents from small firms stating that their projects are too small to implement BIM [39]. Similarly, a number of academic papers [40], [41], [42], have also identified a number similar barriers to BIM implementation on projects specifically with implementation of BIM in small firms, individual resistance to change, associated training and software costs, lack of knowledge and resources.

In addition to the barriers mentioned above, Cavka et al. [43] outline the lack of knowledge from the appointing party in relation to the BIM process along with the lack of adequate information provided to project teams by the appointing party due to poorly structured or non-existent Organisational Information Requirements (OIR). The findings from this paper suggested that current OIR are not clearly defined or structured and are often stored in different locations, sometimes even in the head of Facility Managers of the built asset.

Cavka et al. [43] identified three core challenges to establish clear and defined BIM information requirements: 1. owners are not aware of the complete set of information that is required to support asset lifecycle information, 2. owners do not have enough experience in the BIM process to determine how much of this information can be exchanged and managed through BIM, 3. owners are often unsure about their role in the BIM process. It was also noted in the study that over the past decade, there has been several reports of large scale clients, such as universities, that provide the project team with a set of detailed and defined information requirements and deliverables [44]. However, establishing these requirements so that they inform not only the built asset that is being delivered, but also its digital twin containing relevant project information required by the client is a significant challenge [43].

As outlined in ISO 19650-1: 2018 [37] the Exchange Information Requirements (EIR) outline the multiple types of information related to the delivery and operational phases of an asset by encapsulating the OIR, AIR and PIR. Overall, the content of the EIR covers three key areas of the project; 1. Technical, 2. Management & 3. Commercial, where project requirement details relating to software platforms, deliverables and BIM management processes are all set out.

There is a considerable amount of literature [38], [40], [41], [43], published in the past that has investigated client requirements and steps involved in defining critical project information from the outset of a BIM project. This stage of the process is hugely important and in the past it has often been overlooked. Yet, today a number of common barriers still remain within the BIM information process. The most common barrier that stands in the way of achieving clearly defined client requirements at the beginning of a BIM project is the lack of BIM knowledge / expertise on the client / appointing party's side [43], [45]. Additionally, Ashworth et al. [46] highlight the fact that the appointing party / client are the only stakeholders on the project that untimely understand the exact client's needs. The general consensus from the Focus Group study carried out by Ashworth et al. [46] in relation to the EIR and the right information needed to be captured was that overall due to the lack of BIM knowledge and expertise, it was difficult to tie down the required information needs/outputs and their correct position in the overall BIM Information process. On the contrary, Shakil [40] highlight the individual resistance to change as one of the key barriers to the implementation of BIM. Although, it is not stated as the reason behind the lack of clearly defined client requirements mentioned previously by Cavka et al. [43] but the individual resistance to change is an underlying factor that is often present in research relating to the barriers of BIM implementation and is also one of the key barriers involved in the implementation of lean processes [45], [47], [48].

d) BIM & Lean Synergy

To this point, the literature review section of this study has mainly reviewed the existing literature of both Lean and BIM project delivery as isolated processes. The remaining section of the literature review will assess the limited existing literature relating to the apparent synergy of BIM & Lean.

Lean and BIM principles and processes are contributing to significant changes across all sectors of the Architecture, Engineering, Construction & Operating (AECO) industry. There is a considerable amount of literature that has been carried out to investigate the individual areas of the implementation of lean and BIM processes in the construction stages of projects. Having said that, there appears to be limited research relating to the adoption of these two initiatives in parallel [3]. Although both processes are conceptually independent and separate, synergies between the two processes have been identified. Sacks et al. [3] state that their parallel adoption in state-of-the-art construction practice is a potential source of confusion when assessing their impacts and effectiveness.

A four-year case study carried out by Rischmoller et al. [49] with the aim of evaluating the impact of integrating the areas of both lean and BIM together on a project through means of 'Computer Advanced Visualisation Tools' (CAVT) which used a set of lean principles as the theoretical framework. A key emphasis was put on value generation during the design stage, where it was concluded that the application of CAVT resulted in waste reduction, improved flow and better customer value which in return indicated a strong synergy between lean and CAVT [3]. In addition, Khanzode et al. [50] also tested the possible synergy of lean and BIM by linking Virtual Design & Construction (VDC) with the Lean Project Delivery Process (LPDS) and from a case study carried out during the research confirmed that the application of VDC enhances the LPDS when applied during the correct stages.

Using existing research as the foundation of their study, Sacks et al. [3] expanded their investigation to the potential synergy between both BIM and lean processes with the aim of identifying the positive and negative interactions of lean principles and BIM functionalities adopted on a project. Over the years, authors have collated a list of lean principles. When selecting a set of principles to use for the study, Sacks et al. [3] reviewed lean principles from both general lean production literature Liker [19], [51], [52], and lean construction literature [53], [54] along with Deming [55] 14 principles based on the quality approach. Sacks et al. [3] concluded that there are a total of 55 distinct interactions and also stated that carrying out further research would likely discover more interactions [3].

In the interaction matrix between lean principles and BIM functionalities, Sacks et al. [56] identified 56 total interactions. Most of these interactions were positive interactions between the two processes. One of the more apparent positive interactions was the reduction of cycle times due to the collaborative nature of the BIM process. Additionally, the potential extension of partnerships between disciplines beyond individual projects where integrated systems and processes can be utilised for more efficient and greater value generation for all involved on the project was also noted as another positive interaction. Although there is a synergistic relationship between the lean principle *'Reduce Batch Sizes'* and the BIM functionality *'Automated Generation of drawings & documents'* there is also a negative interaction associated with this interaction due to the ease at which the information can be produced through automation and therefore can enable overproduction of information, which in-return will lead to more versions of the same documentation.

As the overall aim of this paper is to investigate the potential implementation of Lean construction methods during the design stage of the traditional BIM project delivery process. The existing literature reviewed to this point has highlighted several key aspects relating to this topic. Lean is a core idea with the overall aim of maximising customer value while minimising waste [15]. This literature investigated several lean processes implemented within the construction industry, with a detail investigation of the three processes with potential suitability for the design stage as TVD, LPS & SBD. In Addition, the literature reviewed the BIM Project Delivery process in detail. BIM is a digital-based process of designing, constructing, managing and operating both graphical and non-graphical data of a built asset that is stored in a single source digital database or CDE [34]. Several barriers were identified throughout the existing literature, with the most common barriers as follows; 1. Lack of awareness, knowledge & resources, 2. Lack of clearly defined project requirements from the beginning of the project, 3. Individual resistance to change relating to new processes & workflows, 4. Use of collaborative procurement methods. The literature readily available for this topic also identifies a strong synergistic relationship between the two processes. Having said that, academic papers to date that have investigated this relationship have primarily focused on the relationship between lean principles and BIM technologies, rather than the entire BIM process. The literature review has also informed both the pre-interview questionnaire and semi-structed interviews.

III Research Description

The objective of this research area is to explore the following:

i. Critically review the lean processes & principles currently implemented in the Design & Construction Industry.

ii. Critically assess the BIM project delivery process for the design stage.

iii. Seek & evaluate industry opinion in relation to the implementation of Lean processes & principles during the Design Stage of a BIM Project.

iv. Develop a matrix identifying the positive and negative interactions between BIM functions and lean principles during the design stage of a BIM project.

This research was carried out through literature review of currently available published material, and stakeholder questionnaires & semi-structured interviews with industry professionals from various practices in the Irish AEC industry with various levels of BIM implementation.

a) Questionnaire

Participants were chosen from numerous disciplines in the AECO industry in Ireland. The disciplines were as follows;

- Architecture
- Engineering
- Construction
- Operations
- Consultations

In total there were 20 industry professionals that responded to the questionnaire from the disciplines outlined above to give insight to the research area and contribute to the questions used in the interviews. The questionnaire contained questions that covered several themes identified in existing literature as follows;

- Background and professional experience
- Understanding of BIM & Lean processes
- The potential waste in the BIM process
- Synergies & Interaction between BIM & Lean processes

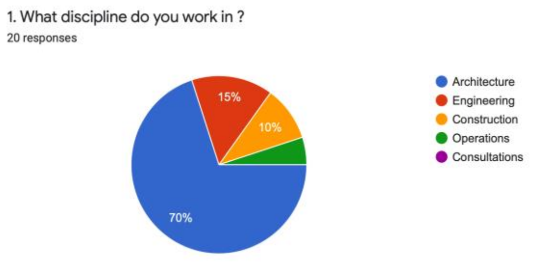

***Figure 3* –** Questionnaire particiapants discipline background

b) Semi-structured Interviews

In total there were two virtual semi-structured interviews carried out through Microsoft Teams with Industry experts in the field of both Lean and BIM. These participants were selected as they are experts in the areas and would provide a good gauge on feedback relating to the themes investigated for this research on behalf of the industry. A set list of interview questions were collated based on existing literature and the feedback from the questionnaire. Both interviews lasted 45 – 60 minutes. The Thematic Analysis [57] methodology approach was selected for the interview process. Each participant was issued the interview questions in advance to enable an open and transparent interview.

c) Interaction Matrix

Sacks et al. [56] proposed a positive and negative interaction between lean principles and BIM functionalities, where the interactions were based on evidence from existing literature. In the original matrix proposed by Sacks et al. several authors in the area of lean principles [51], [19], [52] and in lean construction [53], [54] were reviewed to determine the relevant lean principles that would be incorporated into the study. Additionally, a similar process was also carried out to determine the relevant BIM technologies suitable for the study. The information produced by sacks et al. was used as the foundation for the matrix proposed for this research. The original information was altered to represent the design stage of the BIM project delivery process. Both the lean principles and BIM technologies proposed in the original matrix were reviewed and altered due to relevance with this study. The positive and negative interactions were supported by existing literature and/or industry opinion gained from the questionnaire and interview process.

IV Results

The results discussed are based on thematic analysis of qualitative datasets collected from an online questionnaire with respondents from the AECO industry in Ireland and semi-structured interviews with individuals also from the AECO industry in Ireland. The percentage breakdown of questionnaire participants per discipline were as follow; 70% Architecture, 15% Engineering, 10% Construction and 5% Operations.

Table 01: Dataset sources

Data Source	**Respondents**
Questionnaire	**20**
Semi-structured Interviews	**2**
Total	**22**

a) Awareness of BIM & Lean Processes

The participants were asked several general questions relating to lean construction and BIM project delivery processes currently implemented in the AECO industry to determine the current situation in the industry and to obtain a consensus amongst industry professionals. The participants all have some degree of BIM experience with 12 of the participants having 5-9 years' experience, 6 with 1-4 years and 2 with 10+ years. When asked about the level of BIM implementation in their organisation, 55% of respondents stated that their organisation is well underway with their BIM implementation journey but feel that they still have a long way to go. 15% felt that they are at the beginning of their implementation journey. 25% stated that they have completed their BIM journey with the final 5% stating that they are yet to implement BIM processes in their organisation. 95% of respondents have not used any lean process on a BIM project with only 5% having used TVD, LPS & SBD.

In addition to the questionnaire, both participants involved in the semi-structured interviews work for organisations that have BIM level 2 certification. One participant stated that the BIM project delivery process is implemented on several projects within the organisation and BIM technologies have been rolled out across all projects as an office standard. On the other hand, the second interviewee stated that the roll out of the BIM process on projects within the organisation is Interviewees highlighted LPS as a very useful lean management method that can be implemented during the design stage of a BIM project to assist in the pull-planning method of information management between disciplines. Additionally, to LPS both participants identified TVD as one of the better suited lean processes for the design stage of a BIM project. The participant from the Tier 1 contractor stated that different lean processes are trialled on a project that management feel is suitable and if successful, the process may be rolled out across all project teams. The other interviewee from a Tier 1 Architectural design practice stated that the roll out of the BIM project delivery process is based on a project-by-project basis and heavily relies on the awareness, knowledge and project programme of the particular project team. The implementation in the design practice was aligned to the Toyota Production System (TPS) principles.

b) Barriers to BIM Project Delivery Process

When asked about potential wastes that may exist in the BIM Project Delivery Process for design, 15% of participants said that no wastes exist in the process with 85% identifying multiple wastes that exist. 55% of respondents highlighted a lack of clearly defined information requirements from the appointing party / client as the main cause of waste during the BIM Project Delivery process. Several reasons were suggested as the potential causes of this waste as follows; 1. Lack of knowledge and understanding of the BIM process, 2. Unnecessary levels of BIM information requested from the client without sufficient knowledge of the process to suit their needs. 3. Poorly defined information requirements leading to duplication of efforts for both the design team and construction teams. 4. Lack of buy-in from some design team members which lead to waste of resources and re-work. 5. Lack of planning of stages at the beginning of a project along with not applying the correct roles and responsibilities to BIM teams which can lead to a considerable amount of was for example; having to scrap the planning model at the beginning of the Tender stage and re-starting the model due to a high level of inaccuracies in the input and setting up of the information model. 6. Not utilising a CDE on a project to plan and manage the flow of information between stakeholders on the project.

Similar to the questionnaire participants, the interviewees were asked about their view and experience relating to the potential barriers associated with the BIM project delivery process. Both interviewees highlighted a lack of knowledge and awareness of BIM processes throughout all aspects of the project team, specifically mentioning the client/appointing party as some of the biggest barriers. The tier 1 contractor also highlighted the culture and set up of traditional contracts where the risk is moved from one project team discipline to another, lack of consultation and early engagement of end users and the importance of having the right people at the table to steer the project through the process. Both participants mentioned that resourcing, time and upskilling are the most difficult aspects to implementing new workflows and processes like BIM and lean to organisations especially smaller design and construction organisations where one interviewee highlighted that 80% of architectural practices in Ireland have 1 to 5 employees.

c) BIM & Lean Synergistic Relationship

Time, cost, knowledge / understanding and the ability to identify tangible wastes in the design stage compared to the construction stage of projects were highlighted by 80% of respondents as the main reasons Lean principles and processes are implemented more in the construction stage of projects. 15% of respondents said that the reason for this is because the design teams members do not directly benefit from implementing lean processes during the design stage as it is more difficult to identify tangible wastes during the design stage than construction. Additionally, 40% of responses felt that the different interpretation of information between stakeholders during the design stage is the hidden waste that prevents a successful adoption of these processes. Conversely, one respondent disagreed and said that the lack of adoption lies with main contractors rather than the design team and stated that the contractors are more reluctant to adopt new technologies and methods and revert to traditional methods for measuring and costing.

Both interview participants highlighted the strong synergistic relationship between BIM and lean processes and mentioned the benefits relating to these processes due to the value creation outcome of this relationship. IPD was also identified by both participants as the optimum contract type for the BIM process with one participant stating that an IPD contract drive a better BIM project delivery due to the collaborative nature of the contract with regular coordination and shared risk and reward between project stakeholders. In addition to contracts, both participants mentioned the lean principle; Visual Management as a highly beneficial principle that if implemented more in the design stage of a BIM project could generate increased value generation. Conversely, one interviewee highlighted that although the use of the visual management principle would benefit the design stage, it is crucial to achieve the right balance between pulling valuable information from each discipline to collating too much information that may not be relevant.

d) *Information Requirements*

When asked about the statement that OIR's are often not clearly defined or structured in a single information source which can lead to the failings of BIM projects, 80% of respondents identified this as the biggest issue with the failings of BIM projects and highlighted that lack of knowledge and understanding from the appointing party / client is the biggest issue. Multiple respondents also noted that failing to clearly define the OIR's had a substantial impact on information outputs of project teams and specifically highlighted negative impacts on EIR, AIR, PIR, BEP and information deliverables during key project milestones. One respondent stated that in many cases, client's request the highest levels of BIM requirements without being aware of the time, cost or resources required which in-return translates into a project programme that does not reflect the reality of these requirements and untimely the BIM project fails. On the other hand, 20% of respondents stated that assisting the client with a series of workshops is required to iron out and successfully define the relevant information requirements.

One of the participants said that it is common practice for project teams in their organisation to receive defined project requirements at the beginning of a BIM project especially on projects with blue chip clients as they tend to be more informed. The other interviewee had the opposite experience with BIM projects and stated that it was not common practice for their teams to receive project requirements from the client and has only experienced this on one project to-date. One of the participants referred to a project experience where the project requirements outlined that the design team would develop the design to 60% and the contractor would inherit the design at 60% and develop it to completion or 100%. At the handover stage from the design team to the contractor there was a dispute between the two project teams as the design team said that the development of the design was at 60% and the construction team said the design was only developed to 20%. Due to the reason that the requirements for 60% design were not clearly defined by the client there was a dispute.

e) *Interaction Matrix*

The literature review of this research paper highlighted the limited investigation of the synergy between the BIM and Lean Construction processes as the majority of studies investigated the synergy between lean principles and BIM technologies. Sacks et al. [56] based their matrix on 16 lean principles and 18 BIM functionalities. The matrix proposed as part of this research identified a total number of positive and negative interactions in the matrix (Figure A below) was 34. Of the 34 interactions, 31 were positive meaning the interaction between a lean principle and a BIM process functionality enabled each one to function better. The remaining 3 interactions were negative as the lean principle, BIM functionality or both inhibited the other from providing the most efficient outcome possible. The interaction of the lean principle *'Reduce Cycle Times' (A)* was the lean principle with the most interactions in the matrix with 11. Similarly, the lean principle mentioned above the BIM function *'Online / electronic object-based communication' (8)* was the BIM function that had the most interaction in the matrix also with 11. Figure D in the appendix below provides the evidence of the interactions identified in the matrix with no existing evidence to back up 3 of the interactions proposed (17, 25 & 34). The evidence for interaction 26 & 27 of the matrix was achieved by gaining industry opinion.

V FINDINGS

After analysing the datasets of the existing literature, questionnaire and semi-structured interviews, there were a total of four key themes each consisting of several important findings. The four themes were as follows:

1. Awareness of BIM & Lean Processes
2. Implementation Barriers
3. Information Requirements
4. Synergistic Relationship

1. The study had found that all 22 participants had some level of BIM experience which ranged from 1-4 years' experience to 10+ years' experience. The level of BIM implementation was mixed throughout the participants. Existing literature had identified 11 lean processes that could potentially be utilised in the construction stage of projects and specifically noted TVD, LPS and SBD as three of the most common methods used. Having said that, only 13% of questionnaire and interview participants had worked on projects that had utilised lean processes with the majority of the experience during the construction stage. LPS and TVD were the two most common lean processes identified in the study. Additionally, the use of the word 'lean' may not be suitable as individuals tend to feel that this means cutbacks and job losses. Alternatively, the title *'Operational Excellence'* may be better suited to implementing lean processes in an organisation as it refers continuous improvement to all aspects of the organisation rather than specific areas.

2. There were four barriers identified in multiple academic papers that were said to be the main causes in the failure to implement a successful BIM project delivery process; 1. Lack

of Knowledge 2. Time, Cost & Resources 3. Contract Types 4. Client Requirements. These four barriers were further backed up during the methodology process by industry professionals also highlighting these areas as key barriers to a successful BIM project delivery. In relation to contract types, IPD was identified as an ideal contract type to be implemented during the BIM project delivery process due to its collaborative nature and shared risk and reward. The use of the IPD method is also said to drive better BIM.

3. The lack of clearly defined information requirements at the beginning of the BIM project delivery process has proved to be hugely problematic to-date. The lack of end user involvement at the early design stages, client awareness / knowledge due to misinformation and failure to identify value for the client has resulted in poorly defined or non-existent project requirements that are required to be outlined in the OIR & AIR's as part of the BIM project delivery process.

4. The 34 interactions found in the interaction matrix that consisted of 31 positive interactions and 3 negative interactions further backed up the claims found in the existing literature review relating to the synergistic relationship that is evident between the Lean principles and BIM project delivery process functionalities.

Although there were four key categories of themes that were identified in the literature review and backed up throughout the methodology process, this is not a definitive list of findings from this study (see section VI). These findings were the most prevalent findings identified and investigated as part of this study.

VI Conclusions

The uptake of new processes and workflows in the design and construction industry has increased year on year. BIM project delivery and Lean construction are two examples of processes that are centred around efficient and collaborative methods which are also most prominent in the AECO industry, in-particular the implementation of lean during the construction stage. This paper set out to investigate the current lean construction processes and principles currently implemented during the construction stage and asses their suitability for implementation in design of BIM project delivery. An extensive review of existing literature relating to this topic was carried out and several key themes were identified. The following themes were identified in the literature review; 1. TVD, LPS & SBD are lean construction processes with the potential for implementation during the design stage, 2. Successful implementation of these processes depend on stakeholders identifying and creating value through these processes along with identifying the beneficiary of this value creation, 3. Several key implementation barriers that were identified in the literature review were backed up by the questionnaire and interview participants, 4. Collaborative based procurement methods / contracts like IPD drive a better BIM project delivery process, 5. The synergistic relationship between the two processes that was identified in the existing literature is evident with the 34 interactions highlighted in the proposed matrix in figure A in the appendix below.

A comparison between the literature review and the analysed data from the questionnaire and semi-structured interviews further highlighted these themes and again backed up the findings from this paper which also gave insight into the current situation of these processes in the industry today. Although there is strong evidence of this synergy, the relationship investigated in previous papers primarily focus on the interactions between lean principles and the functions of BIM technologies. This paper begins to investigate the relationship between these lean principles and the BIM project delivery process. Further research into these processes and their synergistic relationship is required to resolve many of the barriers highlighted in this research.

References

[1] M. L. Viana, B. H. W. Hadikusumo, M. Z. Mohammad, and Z. Kahvandi, “Integrated Project Delivery (IPD): An Updated Review and Analysis Case Study,” *J. Eng. Proj. Prod. Manag.*, vol. 10, no. 2, pp. 147–161, 2020, doi: 10.2478/jeppm-2020-0017.

[2] N. Azhar, Y. Kang, and I. U. Ahmad, “Factors influencing integrated project delivery in publicly owned construction projects: An information modelling perspective,” *Procedia Eng.*, vol. 77, pp. 213–221, 2014, doi: 10.1016/j.proeng.2014.07.019.

[3] R. Sacks, B. A. Dave, L. Koskela, and R. Owen, “Analysis framework for the interaction between lean construction and Building Information Modelling,” *Proc. IGLC17 17th Annu. Conf. Int. Gr. Lean Constr.*, pp. 221–234, 2009.

[4] S. Khan and P. Tzortzopoulos, “Effects of the interactions between LPS and BIM on workflow in two building design projects,” *22nd Annu. Conf. Int. Gr. Lean Constr.*

Underst. Improv. Proj. Based Prod. IGLC 2014, pp. 933–944, 2014.

[5] Z. Aziz and A. Tezel, "Lean and BIM – A Synergistic Relationship," *UK Constr. Excell.*, vol. 2016, no. 1, p. 40, 2016, [Online]. Available: https://issuu.com/seamus1972/docs/uk_excellence/41?e=3112020/33110409.

[6] LCIreland, "Lean Construction Ireland - Book of Cases," pp. 26–28, 2018, [Online]. Available: www.leanconstructionireland.ie.

[7] LCIreland, "Lean Construction Ireland - Book of Cases," 2019.

[8] LCIreland, "Lean Construction Ireland Book of Cases 2020," 2020.

[9] R. Sacks, S. Korb, and B. Ronen, *Building Lean, Building BIM*. 2018.

[10] I. H. Md Yusof, M. An, and M. H. Barghi, "Integration of lean construction considerations into design process of construction projects," *Proc. 31st Annu. Assoc. Res. Constr. Manag. Conf. ARCOM 2015*, no. September, pp. 885–894, 2015.

[11] G. Ballard, "Positive vs. Negative Iteration in Design," *Proc. 8th Annu. Conf. Int. Gr. Lean Constr.*, pp. 1–8, 2000.

[12] C. H. Ko and N. F. Chung, "Making design process lean," *22nd Annu. Conf. Int. Gr. Lean Constr. Underst. Improv. Proj. Based Prod. IGLC 2014*, vol. 886, no. 8, pp. 463–474, 2014.

[13] J. Freire and L. F. Alarcón, "Achieving Lean Design Process: Improvement Methodology," *J. Constr. Eng. Manag.*, vol. 128, no. 3, pp. 248–256, 2002, doi: 10.1061/(asce)0733-9364(2002)128:3(248).

[14] P. Tzortzopoulos and C. Formoso, "Considerations on application of lean construction principles to design management," *Proc. IGLC-7*, pp. 335–344, 1999, [Online]. Available: http://iglc.net/Papers/Details/88.

[15] F. A. Emuze and T. A. Saurin, *Value and Waste in Lean Construction*. 2016.

[16] LCI, "What is Lean." https://www.lean.org/whatslean/.

[17] T. Ohno, "Toyota Production System - Beyond Large Scale Production," 1988.

[18] N. Skhmot, "The 8 Wastes of Lean," 2017. https://theleanway.net/The-8-Wastes-of-Lean.

[19] J. K. Liker, *The Toyota way: 14 management principles from the world's greatest manufacturer*. McGraw-Hill, 2004.

[20] D. O'Neill, "Understanding Lean and Lean Construction in Ireland," 2016. https://www.irishbuildingmagazine.ie/2016/04/27/understanding-lean-and-lean-construction-in-ireland/.

[21] G. Ballard, I. D. Tommelein, L. Koskela, and G. A. Howell, "Chapter 15: Lean Construction Tools and Techniques," *Des. Constr. Build. Value*, vol. 15, pp. 227–255, 2002.

[22] S. Khan and P. Tzortzopoulos, "Improving Design Workflow with the Last Planner System: Two Action Research Studies," *Proc. 23rd Annu. Conf. Int. Gr. Lean Constr.*, vol. 1, no. 321, pp. 568–577, 2015.

[23] A. Pennanen, G. Ballard, and Y. Haahtela, "Designing to targets in a target costing process," *Challenging Lean Constr. Think. What Do We Think What Do We Know? - 18th Annu. Conf. Int. Gr. Lean Constr. IGLC 18*, pp. 161–170, 2010.

[24] G. Ballard, "TVD Sutter Health Case Study," 2019.

[25] G. Ballard, "Target Value Delivery of Construction Projects." 2019, [Online]. Available: https://leanconstructionireland.ie/target-value-delivery-of-construction-projects/.

[26] IGLC, "IGLC International Conference Papers," 2021. https://iglc.net/papers.

[27] V. Porwal, "Last Planner System – Areas of Application and Implementation Challenges," 2010.

[28] B. T. Kalsaas, "The Last Planner System Style of Planning: Its Basis in Learning Theory," *J. Eng. Proj. Prod. Manag.*, vol. 2, no. 2, pp. 88–100, 2012, doi: 10.32738/jeppm.201207.0005.

[29] D. Heigermoser, B. García de Soto, E. L. S. Abbott, and D. K. H. Chua, "BIM-based Last Planner System tool for improving construction project management," *Autom. Constr.*, vol. 104, no. June 2018, pp. 246–254, 2019, doi: 10.1016/j.autcon.2019.03.019.

[30] V. Hackett, P. Harte, and G. Chendo, “The Development of Last Planner® System (LPS) Guidance,” 2019.

[31] D. K. Sobek, A. C. Ward, and J. K. Liker, “Toyota ’ s Principles of Set-Based Concurrent Engineering Toyota ’ s Principles of Set-Based Concurrent Engineering Durward K Sobek II,” *Sloan Manage. Rev.*, vol. 40, no. 2, pp. 67–83, 1999.

[32] D. Do, “An Introduction to Set-Based Design,” 2019. https://leanconstructionblog.com/introduction-to-set-based-design.html#:~:text=Set-based Design (SBD),and construction (AEC) industry.&text=Known as point-based design,greater detail of the concept.

[33] V. Sahadevan and K. Varghese, “Stakeholder value evolution, capture and assessment in AEC project design,” *IGLC 2018 - Proc. 26th Annu. Conf. Int. Gr. Lean Constr. Evol. Lean Constr. Towar. Matur. Prod. Manag. Across Cult. Front.*, vol. 1, pp. 549–559, 2018, doi: 10.24928/2018/0403.

[34] NBS, “What is Building Information Modelling (BIM),” 2016. .

[35] HM Government, “2-Construction 2025. Industrial Strategy: Government and industry in partnership,” *UK Gov.*, no. July, p. 78, 2013, [Online]. Available: http://www.bis.gov.uk/assets/biscore/innovation/docs/b/12-1327-building-information-modelling.pdf%5Cnhttps://www.gov.uk/government/publications/construction-2025-strategy%5Cnhttps://www.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/.

[36] J. J. McArthur, “A Building Information Management (BIM) Framework and Supporting Case Study for Existing Building Operations, Maintenance and Sustainability,” *Procedia Eng.*, vol. 118, pp. 1104–1111, 2015, doi: 10.1016/j.proeng.2015.08.450.

[37] BS EN ISO 19650-1:2018, “Organization and digitization of information about buildings and civil engineering works , including building information modelling (BIM) - Information management using building information modelling - Part 1: Concepts and principles,” *Bs En Iso 19650-12018*, pp. 1–46, 2018.

[38] NBS, “NBS National BIM Report 2014,” 2014, [Online]. Available: https://www.thenbs.com/knowledge/nbs-national-bim-report-2017.

[39] NBS, “10th Annual BIM Report,” pp. 1–39, 2020.

[40] S. Ahmed, “Barriers to Implementation of Building Information Modeling (BIM) to the Construction Industry: A Review,” *J. Civ. Eng. Constr.*, vol. 7, no. 2, p. 107, 2018, doi: 10.32732/jcec.2018.7.2.107.

[41] D. Migilinskas, V. Popov, V. Juocevicius, and L. Ustinovichius, “The benefits, obstacles and problems of practical bim implementation,” *Procedia Eng.*, vol. 57, pp. 767–774, 2013, doi: 10.1016/j.proeng.2013.04.097.

[42] M. Bolpagni, L. Burdi, and A. L. C. Ciribini, “The implementation of building information modelling and lean construction in design firms in Massachusetts,” *IGLC 2017 - Proc. 25th Annu. Conf. Int. Gr. Lean Constr.*, vol. II, no. July, pp. 235–242, 2017, doi: 10.24928/2017/0310.

[43] H. B. Cavka, S. Staub-French, and E. A. Poirier, “Developing owner information requirements for BIM-enabled project delivery and asset management,” *Autom. Constr.*, vol. 83, no. June, pp. 169–183, 2017, doi: 10.1016/j.autcon.2017.08.006.

[44] K. Kensek, “BIM guidelines inform facilities management databases: A Case Study over Time,” *Buildings*, vol. 5, no. 3, pp. 899–916, 2015, doi: 10.3390/buildings5030899.

[45] S. Macloughlin, “Overcoming Resistance To BIM: Aligning A Change Management Overcoming Resistance To BIM: Aligning A Change Management Method with A BIM Implementation Strategy Method with A BIM Implementation Strategy,” 2019, [Online]. Available: https://arrow.tudublin.ie/schmuldistcap.

[46] S. Ashworth, M. Tucker, C. Druhmann, and M. Kassem, “Integration of FM expertise and end user needs in the BIM process using the Employer’s Information Requirements (EIR),” *Proc. CIB World Build. Congr.*, vol. 5, no. May, pp. 1–12, 2016.

[47] H. G. Bayhan, S. Demirkesen, and E. Jayamanne, “Enablers and Barriers of Lean Implementation in Construction

Projects," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 471, no. 2, 2019, doi: 10.1088/1757-899X/471/2/022002.

[48] B. Dave, S. Boddy, and L. Koskela, "Challenges and opportunities in implementing lean and BIM on an infrastructure project," *21st Annu. Conf. Int. Gr. Lean Constr. 2013, IGLC 2013*, pp. 60–69, 2013.

[49] L. Rischmoller, L. F. Alarcón, and L. Koskela, "Improving Value Generation in the Design Process of Industrial Projects Using CAVT," *J. Manag. Eng.*, vol. 22, no. 2, pp. 52–60, 2006, doi: 10.1061/(asce)0742-597x(2006)22:2(52).

[50] A. Khanzode, M. Fischer, D. Reed, and G. Ballard, "A Guide to Applying the Principles of Virtual Design & Construction (VDC) to the Lean Project Delivery Process," 2006.

[51] R. J. Schonberger, *World Class Manufacturing : The Next Decade*. 1996.

[52] J. P. Womack and D. T. Jones, *Lean Thinking : Banish Waste and Create Wealth in Your Corporation*. 2003.

[53] L. Koskela, "Application of the new production philosophy to construction," vol. 72, 1992.

[54] L. Koskela, "An exploration towards a production theory and its application to construction," 2000, [Online]. Available: https://aaltodoc.aalto.fi:443/handle/123456789/2150.

[55] E. W. Deming, "Improvement of quality and productivity through action by management," 1982.

[56] R. Sacks, L. Koskela, B. A. Dave, and R. Owen, "Interaction of lean and building information modeling in construction," *J. Constr. Eng. Manag.*, vol. 136, no. 9, pp. 968–980, 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000203.

[57] S. Damayanthi, "Thematic Analysis of Interview Data in the Context of Management Controls Research," *Themat. Anal. Interview Data Context Manag. Control. Res.*, 2019, doi: 10.4135/9781526474858.

APPENDIX

LEAN PRINCIPLES / BIM PROJECT DELIVERY PROCESS FOR DESIGN STAGE FUNCTIONS		Reduce Cycle Times	Reduce Batch Sizes	Increase Flexibility	Select an appropriate production control approach	Standardise	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 & Validate	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
Visualisation of form	1								2	3		7	4	3	
Rapid generation of design alternatives	2	10						5	6						
Re-use of model data for predictive analysis	3	8, 10		25					6	1	1, 9	1	4		
Maintenance of information and design model integrity	4	10										7	8		
Automated generation of drawings & documents	5	10, (26)	27						28						
Collaboration in Design	6	11, 12		15	(17)				17	20		29	22	24	
BIM Documentation Process	7	30				31				32			33	24	34
Online / electronic object-based communication	8	13, 14	14		16	18		16, 18	(19)			21	23	24	

Figure A – Interaction Matrix

BIM FUNCTIONALITY – BIM PROJECT DELIVERY

VISUALISATION OF FORM (FOR AESTHETIC AND FUNCTIONAL EVALUATION) — 1

All BIM systems provide the ability to render the designs with some degree of realism, making building designs more accessible to non- technical project participants and stakeholders than is possible with technical drawings.

RAPID GENERATION OF MULTIPLE DESIGN ALTERNATIVES — 2

Designers can manipulate design geometry efficiently by taking advantage of the parametric relationships and behavioural 'intelligence', which maintain design coherence, and of automated generation and layout of detailed components (e.g. automated connection detailing in steel construction). This was not possible with computer-aided drafting (CAD) systems.

USE OF MODEL DATA FOR PREDICTIVE ANALYSIS OF BUILDING PERFORMANCE — 3

a. Some BIM software products have engineering analysis tools such as energy analyses built-in, and most can export relevant pre-processed data for import to external third- party analysis tools. Varying degrees of human effort are needed to adapt the exported data to the forms required by the analysis tools, and different degrees of rework are required to change the analysis models whenever the building model is changed. Nevertheless, the procedures are more productive, less error prone and quicker than compilation of the analysis models from scratch.

b. Automated life-cycle and construction cost estimation with links to online sources of cost data.

c. Automated evaluation of conformance to program/client value and code compliance checking using rule processing. A recent comprehensive review (Eastman et al. 2008) shows that while this functionality is still limited in scope, its development is well beyond the proof of concept stage.

MAINTENANCE OF INFORMATION AND DESIGN MODEL INTEGRITY — 4

This capability is achieved because BIM tools store each piece of information once, without the repetition common in drawing systems where the same design information is stored in multiple drawings or drawing views (such as on a plan, an elevation and a detail sheet). Geometric integrity is also enhanced where the automatic clash-checking capabilities of model integration software tools are used to identify and remove physical clashes between model parts.

AUTOMATED GENERATION OF DRAWINGS AND DOCUMENTS — 5

Different BIM software offer varying degrees of automation for initial generation of drawings and documents, with most needing at least some user input for custom annotation. By definition, a BIM system is one that automatically propagates any model changes to the reports, thus automatically maintaining integrity between the model and the reports (Eastman et al. 2008, p. 16). Some, but not all, also offer full bi-directional editing, where the model can be edited directly from model object links embedded in drawings.

COLLABORATION IN DESIGN — 6

Is expressed in two ways: 'internally', where multiple users within a single organisation or discipline edit the same model simultaneously, and 'externally', where multiple modelers simultaneously view merged or separate multi-discipline models for design coordination. Whereas in the internal mode objects can be locked to avoid inconsistencies when objects might be edited to produce multiple versions, in the external mode only non-editable representations of the objects are shared, avoiding the problem, but enforcing the need for each discipline to modify its own objects separately before checking whether conflicts are resolved.

ONLINE / ELECTRONIC OBJECT-BASED COMMUNICATION	7
At present, online communication is largely limited to the use of project intranets and more sophisticated model-servers. However, more sophisticated systems that integrate product information in BIM tools with process information from enterprise-wide information systems have moved beyond early research and have been implemented e.g. Autodesk BIM 360.	
STANDARDISED PROCESS - DOCUMENTATION & WORKFLOWS	8
Standardisation of information production and the process of information flow between project stakeholders during the design stage of the BIM project delivery process has also moved beyond early research and is being implemented throughout many aspects of the AECO industry largely due to the publication of ISO 19650 standards and the Irish annex published in 2021.	

Figure B – BIM Project Delivery Process Functionalities

LEAN PRINCIPLES	
	LETTER REF.
PRINCIPLE AREA: FLOW PROCESS	
REDUCE CYCLE TIMES:	**A**
In design, the reduction of cycle times should focus on the analysis of total design duration and the stage of design with the task in-hand.	
REDUCE BATCH SIZES (STRIVE FOR SINGLE PIECE FLOW)	**B**
Reduce batch sizes or striving for single piece flow, is an effective technique for reducing the expansion of cycle times due to batching. In design, the design of repetitive spaces, such as apartment types can be categorised into batches/groups of the same layout type.	
INCREASE FLEXIBILITY:	**C**
Here flexibility may be associated with iterations of design through means of design options. Flexibility reduces cycle times and also simplifies the production system. In design, this may be achieved by developing several possible options at high-level during the earlier stages of design.	
SELECT AN APPROPRIATE PRODUCTION CONTROL APPROACH	**D**
In a pull system, a productive activity is triggered by the demand of a downstream customer, whereas in a push system, a plan pushes activities into realization. The pull system has come to be closely associated to lean. However, typically production control systems are mixed push-pull systems, and the task is to select the best method for each stage of production. Levelling of production facilitates the operations of a pull system. In design & construction, the push system is realised through plans and schedules. The look-ahead procedure in the Last Planner System of production control provides an example of pulling.	
STANDARDISE	**E**
Standardisation of work serves several goals. Both temporal and product feature variability can be reduced, and continuous improvement is enabled. Employees are also empowered to improve their work.	
CONTINUOUS IMPROVEMENT	**F**
Through continuous improvement, variability can be reduced and the on-going improvement of the processes can be achieved through incremental and breakthrough improvements. The continuous improvement model; Plan-Do-Check-Act is one of the most widely used quality assurance methods available.	
USE VISUAL MANAGEMENT	**G**
Visual management is closely connected to standardisation, where visualisation of production methods offers easy access to standards and supports compliance. It is also closely connected to continuous improvement, in that visualisation of production processes enables perception by workers of the process state and measures of improvement.	
DESIGN THE PRODUCTION	**H**

SYSTEM FOR FLOW AND VALUE	
This principle highlights the importance of production system design durig the design stage. Generally, criteria derived from the two concepts of production should be used in this endeavour. Another important issue is that production system design should support production control and continuous improvement. There are several heuristics for production system design, advising towards simplification, use of parallel processing and use of only reliable technology. From the viewpoint of value, ensuring the capability of the production system is important.	
PRINCIPLE AREA: VALUE GENERATION PROCESS	
ENSURE COMPREHENSIVE REQUIREMENTS CAPTURE	**I**
This is the first principle addressing solely the value generation concept. For obvious reasons, value generation requires comprehensive requirements capture – in practice, this is a notoriously problematic stage.	
FOCUS ON CONCEPT SELECTION	**J**
During the design stage the development of different concepts and their evaluation should be addressed with necessary emphasis, as there is a natural tendency to rush to detail design. Set based design is an application of this principle that is useful for building design (Parrish et al. 2007).	
ENSURE REQUIREMENT FLOW DOWN	**K**
The next challenge from the point of view of value generation is to ensure that all requirements that add customer value flow down to the point where the requirements that enable customer value are achieved to the appropriate information level.	
VERIFY & VALIDATE	**L**
The value generation principle, well known from the V model of systems engineering (Stevens et al. 1998), reminds us that intent is not enough. All designs should be verified against specifications and validated against customer requirements.	
PRINCIPLE AREA: PROBLEM SOLVING	
DECIDE BY CONSENSUS, CONSIDER ALL OPTIONS	**M**
This principle derives from the practice of Toyota (Liker 2006). By extending the circle of decision makers, a wider knowledge base can be ensured for the decisions. By extending the number of options considered, the probability of finding the practically best solution is increased.	
PRINCIPLE AREA: DEVELOPING PARTNERS	
CULTIVATE AN EXTENDED NETWORK OF PARTNERS	**N**
This principle implies that an extended network of partners should be built, challenged and helped to improve. In design, this can either happen in the framework of one project (alliancing), or on a longer term basis (framework agreements).	

Figure C – Lean Principles

INTERACTIONS EXPLAINED		
DESCRIPTION	EVIDENCE	INDEX
Due to better appreciation of design at an early stage, 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 later project stages.	(Eastman et al. 2008 p.390; Manning and Messner 2008)	1
Building systems are becoming increasingly	(Eastman et al. 2008	2

complex. Even trained professionals have difficulty generating accurate mental models with drawings alone. BIM simplifies the task of understanding designs, which helps project teams deal with complex products.	p.382)	
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.	(Eastman et al. 2008 p.378; Manning and Messner 2008)	3
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.	(Eastman et al. 2008 p.390; Khanzode et al. 2006	4
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.	(Eastman et al. 2008 p.378)	5
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 or Solibri etc. as exemplified in 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.	(Eastman et al. 2008 p.329; Khemlani 2009)	6
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.	(Eastman et al. 2008 p.422)	7
Use of software capable of model integration (such as Solibri/Navisworks) to merge models, identify clashes, and resolve them through iterative refinement of the different discipline specific models results in almost error free installation on site.	(Eastman et al. 2008 p.431)	8
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 optimisation procedures (such as genetic algorithms).	(Eastman et al. 2008 p.445)	9

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.	(Eastman et al. 2008 p.386)	10
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.	(Khemlani 2009)	11
Model-based coordination between disciplines (including clash-checking) is automated and so requires a fraction of the time needed for coordination using CAD overlays.	(Eastman et al. 2008 p.422)	12
Where process status is visualized through a BIM model, such as in the KanBIM system, 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.	(Sacks et al. 2010)	13
Online visualisation and management of process can help implement production strategies designed to reduce work-in-process inventories and production batch sizes.	(Sacks et al. 2009)	14
Design coordination between multiple design models using an integrated model viewer in a collaborative work environment, such as those described in Khanzode et al. (2006), enables design teams to bring multi-disciplinary knowledge and skills to bear in a parallel process.	(Khanzode et al. 2006)	15
Process visualisation and online communication of process status are key elements in allowing design teams to prioritise their subsequent work tasks in terms of their potential contribution to ensuring a continuous subsequent flow of work, thus implementing a pull flow.	(Sacks et al. 2009)	16
Multiple users working on the same model simultaneously enables sharing of the workload evenly between project teams.	(Not yet available)	17
Online access to production standards, product data and company protocols helps institutionalise 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.	(Sacks et al. 2010)	18
These applications cannot be considered mature technology.	(Manning and Messner	19

	2008)	
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.	(Eastman et al. 2008 p.349)	20
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).	(Sacks et al. 2010)	21
Clash-checking and solving other integration issues verifies and validates information.	(Sacks et al. 2010)	22
Visualisation of proposed schedules and visualisation of ongoing processes verifies and validates process information.	(Sacks et al. 2010)	23
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.	(Sacks et al. 2010)	24
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	(Not yet available)	25

more detailed analyses.		
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.	(Shearman, B. 2021)	26
Automated generation of drawings, enables review and verification with other documents e.g. specification to be performed in smaller batches because the information can be provided on demand.	(Shearman, B. 2021)	27
Automated drawing generation improves engineering capacity when compared with 2D drafting, and it is a more reliable technology because it produces properly coordinated drawings sets.	(Sacks et al. 2010)	28
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.	(McPartland, R. 2014)	29
The BIM Process directly benefits from concurrent engineering (CE) management principles by modifying the waterfall management (ref VO 2007) process into a iterative and integrated collaborative process. Similar management processes to CE in the indystry are	(Talebi, S. 2014	30

Design & Build (DB) and Integrated Project Delivery (IPD).		
In the design stage of the BIM process the standardisation of repetitive workflows i.e. the sharing of project information, the supporting BIM documentation and the live collaboration of project stakeholders contributes to the elimination of waste during the design stage and does not prevent design development.	(ISO 19650-1 &2:2018)	31
At the beginning of the BIM project delivery process the appointing party is responsible for outlining the information requirements for the project. This consists of the Exchange Information Requirements (EIR), Asset Information Requirements (AIR) and a list of defined Project Information Requirements (PIR) at the end of each work stage each of which are developed on the foundation of the Organisational Information Requirements (OIR). Often, an individual or organisation is nominated to put the information for the project on behalf of the client or appointing party.	(ISO 19650-1:2018 & Ashworth et al. 2016)	32
The Common Data Environment (CDE) concept consists of information that falls into four possible states; Work In Progress (WIP), Shared, Published or Archived. As all of the information is stored within the CDE it enables an efficient process for reviewers to verify and validate information that is passed through the approval gates. The CDE contains a record of each document stored in the CDE which makes access to the history of the document readily available to the relevent stakeholder.	(ISO 19650-1:2018 - Chapter 12)	33
Developing a network of partners that have the BIM project delivery process implemented into their workflows will enable a more efficient process between project stakeholders and reduce a considerable amount of waste through collaboration during the design stage. For example, on the design team a list of consultants (e.g. Facade, Acoustic, DAC, FSC & Landscape Architect) that have these processes in-place will maximise the value produced due to aligned processes & workflows whilst contributing to the reduction of waste.	(Not yet available)	34

Figure D – Interactions Explained