

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**A DELPHI STUDY EXAMINING THE INTERACTION OF BUILDING
INFORMATION MODELLING AND LEAN CONSTRUCTION**



M.Sc. THESIS

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Department of Architecture

Project and Construction Management

March, 2021

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**YAPI BİLGİ MODELLEMESİ İLE YALIN İNŞAATIN ETKİLEŞİMİNE
YÖNELİK BİR DELPHI ÇALIŞMASI**

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To my family,



FOREWORD

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ABBREVIATIONS

AEC	: Architecture, Engineering and Construction
BIM	: Building Information Modelling
BoQs	: Bill of Quantities
BSc	: Bachelor of Science
CAD	: Computer Aided Design
CAVT	: Computer Advanced Visualisation Tools
CDE	: Common Data Environment
CPM	: Critical Path Method
EDM	: Express Data Manager
IFC	: Industry Foundation Classes
IGLC	: International Group for Lean Construction
IPD	: Integrated Project Delivery
IRA	: Inter-rater Agreement
ISO	: International Organization for Standardization
IT	: Information Technology
JIT	: Just-in-time
KanBIM	: Kanban using BIM
LC	: Lean Construction
LPS	: Last Planner System™
MEP	: Mechanical, Electrical and Plumbing
MSc	: Master of Science
NBIMS-US	: National BIM Standard-United States
NPD	: New Product Development
PhD	: Doctor of Philosophy
PPC	: Percent Plan Completed
QTO	: Quantity take-off
SD	: Standard Deviation
SEM	: Structural Equation Modelling
SMC	: Solibri Model Checker
TFV	: Transformation, Flow, Value

TPS	: Toyota Production System
TQM	: Total Quality Management
UK	: United Kingdom
US	: United States
WIP	: Work-in-progress



SYMBOLS

A	: Maximum scale value
B	: Minimum scale value
M	: Mean value of that factor
n	: The number of variables
W	: Kendall's coefficient of concordance
α	: Cronbach's Alpha
σ_x^2	: The total variance of the overall score.
σ_i^2	: The score variations on each variable
a_{wg}	: The inter-rater agreement statistics (IRA)
$\bar{R}_i$	: The average of the ranks assigned to the i^{th} item
$\bar{R}$	: The average of the ranks assigned to all items



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A DELPHI STUDY EXAMINING THE INTERACTION OF BUILDING INFORMATION MODELLING AND LEAN CONSTRUCTION

SUMMARY

Building Information Modelling (BIM) and lean construction (LC) are considered as disruptive approaches. The Architecture, Engineering, and Construction (AEC) industry has fallen way behind other industries in the adoption of new technologies and methods. The AEC industry is considered wasteful and non-productive compared to other industries. In the AEC industry, efforts are spent on activities that do not add value to the end-users. Moreover, segmentation in the AEC industry and lack of interoperability among the software fortifies the information loss during the various phases of construction.

BIM and LC are practiced independently and have shown success and acquired recognition among the industry. However, the adoption of both simultaneously has attracted less attention. BIM is a new approach and technology in the AEC industry while LC is a new management approach targeting wastes. This study aims to study what their interactions are by obtaining experts' opinions who have experience of BIM and LC implementation.

A comprehensive background study and literature review were carried out in the first stage of the thesis. In the background study, VOSviewer was applied to analyse the network of co-authorship, country/region, published journal, co-citation, and co-occurring keywords. Moreover, a two-round Delphi survey was conducted to extract the expert's judgment about BIM and LC.

Moreover, a two-round Delphi survey was undertaken to extract the expert's judgment about BIM and LC. The expert panel consisted of 13 members whose roles were mainly BIM manager, BIM coordinator, and BIM modeler. The aim was to aggregate the consensus between a panel of experts on the interaction of BIM and LC. The Delphi survey was designed by a detailed analysis of extant literature. The framework proposed by Sacks et al. (2010) was adopted as the Delphi survey questionnaire.

In the first-round Delphi survey, some demographic information and a matrix checklist which listed BIM functionalities and lean principles were sent to expert panels. They were asked to tick interaction if they think there exists any. Subsequently, the result of the first-round Delphi survey was analysed and the feedback was given to the participants by keeping the anonymity of participants. They were requested to change or adjust their answer wherever they think it fits in the second-round. In the second-round Delphi survey, they were asked to rate the interaction on a 5-point Likert scale with 1 = strongly disagree and 5 = strongly agree.

46.2% percent of the experts had an architectural background, while 46.2% percent had a civil engineering, and 7.7% had an electrical engineering background. All except one of the panellists are adopting BIM and lean in their companies (i.e., 92.3% of the participants are using BIM-LC). 23.07% percent of the experts is BIM manager, 38.46% percent is BIM modeller and 38.46% percent is BIM coordinator. 7.7%

percent has 11-15 years of experience, 3.8% percent has 6-10 years of experience, 46.2% percent has 2-5 years of experience, and 15.4% percent has less than 2 years of experience.

The result of the two-round Delphi survey was validated by statistical approaches such as Cronbach's alpha reliability test, Kendall's coefficient of concordance and inter-rater agreement (IRA) statistics. The Cronbach's alpha (α) is acceptable with the value of 0.703. The Shapiro-Wilk test showed that the dataset is non-normally distributed so non-parametric statistical approach is adopted throughout the validation.

The result of the mean score and standard deviation analysis demonstrated that the mean scores and standard deviation for the interactions of eight BIM functionalities and sixteen lean principles identified in the second-round Delphi survey ranges from [$\mu = 4.85$, $\sigma = 0.376$ and $\sigma^2 = 0.141$] for "A1: Visualization of form and Reduce variability" to [$\mu = 1.08$, $\sigma = 0.277$ and $\sigma^2 = 0.077$] for "B7: Rapid generation and Evaluation of construction plan alternatives and Reduce cycle times". Kendall's coefficient (W) with a value of 0.842 indicates a solid consensus on interactions among BIM functionalities and lean principles. Moreover, the IRA analysis has shown the level of agreement and ranked the interactions from highest to lowest.

The first ten interactions of BIM and LC are: "visualisation of the form" and "reduce variability" and "reuse of model data for predictive analyses" and "reduce cycle times" with a mean score of 4.85 ranked first interactions. Interactions with a mean score of 4.77 which ranked second among the others are; "online/electronic object-based communication" and "reduce variability", "collaboration in design and construction" and "ensure requirement flow down", and "collaboration in design and construction" and "reduce variability".

Sets of interactions that stand in the third place are "visualisation of the form" and "use visual management", "rapid generation of multiple design alternatives" and "reduce cycle times", "automated generation of drawings and documents" and "reduce cycle times", and "online/electronic object-based communication" and "increase flexibility" have got an equal mean score of 4.69.

Another eclectic of interactions with a mean score of 4.62 are "maintenance of information and design model integrity" and "ensure requirements flow down", "online/electronic object-based communication" and "cultivate an extended network of partners", "visualisation of the form" and "go and see for yourself", "reuse of model data for predictive analyses" and "design the production system for flow and value".

Although a plethora of positive BIM and LC interactions, some negative interactions have adverse effects. "Rapid generation and evaluation of construction plan alternatives" have a negative interaction with "reduce cycle times". Rapid generation of construction plan alternatives increases the inventory of designs which is a surge in cycle times. "Online/electronic object-based communication" and "design the production system for flow and value" have a negative interaction. Design the production system for flow and value requires applications of reliable technology, however, BIM is not mature yet.

The study demonstrates a mutual and profound collection of interactions among BIM functionalities and lean principles. The experts agree that BIM and LC offer various benefits for the AEC industry if administered both together. BIM proposes a myriad of functionalities that will enhance the design, construction, and operation of a facility. On other hand, LC is a new management approach that aims to minimise wastes

through continuous improvement and respect for the people and improve value for the customer.

The limitations of the study include the limited data regarding the holistic study of BIM and LC integration. Therefore, the Delphi method was used to obtain agreement among the experts on the interaction of BIM and LC. Future studies should adopt a quantitative research methodology for validation of the proposed framework. Furthermore, the study was carried out in Turkey and could be generalised to other countries too. Other techniques or tools than Delphi method which was attempted to obtain group consensus, can also be utilised to reflect other interactions for further studies.





YAPI BİLGİ MODELLEMESİ İLE YALIN İNŞAATIN ETKİLEŞİMİNE YÖNELİK BİR DELPHI ÇALIŞMASI

ÖZET

Yapı Bilgi Modellemesi (BIM) ve yalın inşaat (LC) yeni yaklaşımlar olarak karşımıza çıkmaktadır. Yeni teknolojilerin benimsenmesinde diğer endüstrilerin gerisinde kalan Mimarlık, Mühendislik ve İnşaat (AEC) endüstrisi, diğer endüstrilere kıyasla savurgan olmakla beraber üretkenliği de düşüktür. AEC endüstrisinde, son kullanıcılara değer katmayan faaliyetler için çaba harcanmaktadır. Ayrıca, AEC endüstrisindeki segmentasyon ve yazılımlar arasında birlikte çalışabilirliğin olmaması, inşaatın çeşitli aşamalarında bilgi kaybına yol açmaktadır.

BIM ve LC genellikle bağımsız olarak uygulanmakta ve sergiledikleri başarılı sonuçlar ile sektörde tanınırlık kazanmıştır. Her ikisinin aynı anda benimsenmesi ise daha az ilgi çekmektedir. BIM, AEC endüstrisinde yeni bir yaklaşım ve teknoloji iken LC atıkları hedefleyen yeni bir yönetim yaklaşımıdır. Bu çalışma, BIM ve LC uygulaması deneyimine sahip uzmanların görüşlerini alarak etkileşimlerinin neler olduğunu incelemeyi amaçlamaktadır.

Tez çalışmasının ilk aşamasında kapsamlı bir arka plan çalışması ve literatür taraması yapılmıştır. Arka plan çalışmasında, VOSviewer ortak yazarlık, ülke/bölge, yayınlanan dergi, ortak alıntı ve birlikte ortaya çıkan anahtar kelimeler ağını analiz etmek için kullanılmıştır.

Ayrıca, BIM ve LC hakkında uzmanın görüşünü çıkarmak için iki aşamalı bir Delphi anketi yapıldı. Uzman paneli, rolleri çoğunlukla BIM yöneticisi, BIM koordinatörü ve BIM modelleyicisi olan 13 üyeden oluşuyordu. Amaç, BIM ve LC'nin etkileşimi konusunda bir uzmanlar paneli arasındaki fikir birliğini toplamaktır. Delphi anketi, mevcut literatürün ayrıntılı bir analizi ile tasarlanmıştır. Sacks ve diğerleri tarafından önerilen çerçeve. (2010) Delphi anketi anketi olarak kabul edildi.

İlk tur Delphi anketinde, bazı demografik bilgiler ve BIM işlevlerini ve yalın ilkeleri listeleyen bir matris kontrol listesi uzman panellerine gönderildi. Var olduğunu düşünüyorlarsa etkileşimi işaretlemeleri istendi. Ardından, ilk tur Delphi anketinin sonucu analiz edilmiş ve katılımcıların anonimliği korunarak katılımcılara geri bildirim verilmiştir. İkinci turda uygun olduğunu düşündükleri her yerde yanıtlarını değiştirmeleri veya ayarlamaları istendi. İkinci tur Delphi anketinde, etkileşimi 1 = kesinlikle katılmıyorum ve 5 = kesinlikle katılıyorum şeklinde 5 puanlık bir Likert ölçeğine göre derecelendirmeleri istendi.

Uzmanların %46,2'si mimarlık geçmişine, % 46,2'si inşaat mühendisliği geçmişine ve %7,7'si elektrik mühendisliği geçmişine sahiptir. Panelistlerden biri hariç tümü şirketlerinde BIM ve yalın yaklaşımı benimsemektedir. Bir diğer deyişle, katılımcıların %92,3'ü BIM ve LC kullanmaktadır. Uzmanların %23.07'si BIM yöneticisi iken %38.46'sı BIM modelleyicisi ve %38.46'sı BIM koordinatörüdür. %7,7'si 11-15 yıllık

deneyime, %3,8'i 6-10 yıllık deneyime, %46,2'si 2-5 yıllık deneyime ve %15,4'ü 2 yıldan az deneyime sahiptir.

İki aşamalı Delphi anketinin sonucu, Cronbach alfa güvenilirlik testi, Kendall'ın uyum katsayısı ve değerlendiriciler arası anlaşma (IRA) istatistikleri gibi istatistiksel yaklaşımlarla doğrulanmıştır. 0,703 olan Cronbach alfa (α) değeri kabul edilebilir olarak değerlendirilebilir. Shapiro-Wilk testi, veri setinin normal olmayan bir şekilde dağıldığını göstermiştir, bu nedenle parametrik olmayan istatistiksel yaklaşım doğrulama boyunca benimsenmiştir.

Ortalama puanın ve standart sapma analizinin sonucu, ikinci tur Delphi anketinde belirlenen sekiz BIM işlevselliği ve on altı yalın ilkenin etkileşimleri için ortalama puanların ve standart sapmanın [$\mu = 4,85$, $\sigma = 0,376$ ve σ^2 arasında değiştiğini göstermiştir. = 0.141] için “A1: Formun görselleştirilmesi ve değişkenliğin azaltılması” için “B7: Hızlı üretim ve inşaat planı alternatiflerinin değerlendirilmesi ve döngü sürelerinin azaltılması” için [$\mu = 1.08$, $\sigma = 0.277$ ve $\sigma^2 = 0.077$] 'ye. 0,842 değerli Kendall'ın katsayısı (W), BIM işlevleri ve yalın ilkeler arasındaki etkileşimler konusunda sağlam bir fikir birliğine işaret etmektedir. Dahası, IRA analizi, anlaşma seviyesini göstererek etkileşimleri en yüksekten en düşüğe doğru sıralamaktadır.

BIM ve LC'nin ilk on etkileşimi: ortalama 4,85 puanla “formun görselleştirilmesi” ve “değişkenliğin azaltılması” ve “tahmine dayalı analizler için model verilerinin yeniden kullanılması” ve “döngü sürelerinin kısaltılması” ilk sıradaki etkileşimler olarak karşımıza çıkmaktadır. İkinci sırada yer alan ortalama puanı 4,77 olan etkileşimler ise “çevrimiçi/elektronik nesne tabanlı iletişim” ve “değişkenliği azaltma”, “tasarım ve yapımda işbirliği” ve “gereksinim akışını sağlama” ve “tasarım ve yapımda işbirliği” ve “değişkenliği azaltma”dır.

Üçüncü sırada yer alan etkileşim kümeleri: “formun görselleştirilmesi” ve “görsel yönetimin kullanılması”, “birden çok tasarım alternatifinin hızlı oluşturulması” ve “döngü sürelerinin azaltılması”, “otomatikleştirilmiş çizim ve belge oluşturma” ve “döngü sürelerini azaltma” şeklindedir. “Çevrimiçi/elektronik nesne tabanlı iletişim” ve “esnekliği artırma” eşit ortalama puana sahip olup bu değer 4,69'dur.

Ortalama puanı 4,62 olan bir diğer etkileşim eklektiği, “bilgi ve tasarım modeli bütünlüğünün korunması” ve “gereksinimlerin aşağı doğru akmasını sağlama”, “çevrimiçi/elektronik nesne tabanlı iletişim” ve “genişletilmiş bir ortaklar ağı geliştirme”, “form” ve “gidin ve kendiniz görün”, “tahmine dayalı analizler için model verilerinin yeniden kullanımı” ve “akış ve değer için üretim sistemini tasarlayın”dır.

Çok sayıda pozitif BIM ve LC etkileşimleri olmasına rağmen, bazı olumsuz etkileşimler de söz konusudur. “İnşaat planı alternatiflerinin hızlı oluşturulması ve değerlendirilmesi” ile “döngü sürelerini kısaltmak” olumsuz bir etkileşime sahiptir. Hızlı inşaat planı alternatifleri üretimi, döngü sürelerinde bir artış olan tasarımların envanterini artırmaktadır. “Çevrimiçi/elektronik nesne tabanlı iletişim” ve “üretim sistemini akış ve değer için tasarlama” olumsuz bir etkileşime sahiptir. Üretim sistemini akış ve değer için tasarlamak, güvenilir teknoloji uygulamalarını gerektirmektedir ancak BIM henüz olgunlaşma seviyesinde değildir.

Bu tez çalışması, BIM işlevleri ve yalın ilkeler arasında karşılıklı ve derin bir etkileşim koleksiyonunu göstermektedir. Uzmanlar, BIM ve LC'nin, her ikisinin birlikte yönetilmesi durumunda AEC endüstrisi için çok sayıda fayda sağladığı konusunda hemfikirdir. BIM, bir tesisin tasarımını, yapımını ve işletimini geliştirecek sayısız işlev

önermektedir. Öte yandan LC, sürekli iyileştirme ve insana saygı ile atıkları en aza indirmeyi ve müşteri için değeri artırmayı hedefleyen yeni bir yönetim yaklaşımıdır.

BIM ve LC entegrasyonunun bütünsel çalışmasına ilişkin sınırlı veri çalışmanın kısıtlamaları arasında yer almaktadır. Bu nedenle, BIM ve LC'nin etkileşimi konusunda uzmanlar arasında fikir birliği elde etmek için Delphi yöntemi kullanılmıştır. Gelecekteki çalışmalar için, önerilen çerçevenin doğrulanması için nicel bir araştırma metodolojisi benimsenebilir. Çalışma Türkiye'deki durumu yansıtmakla beraber diğer ülkeler için de uygulanabilir. Grup fikir birliği elde etmeye çalışılan Delphi yöntemi dışındaki diğer teknikler veya araçlar, daha sonraki çalışmalar için diğer etkileşimleri yansıtmak için de kullanılabilir.





1. INTRODUCTION

Traditionally, the architectural, engineering and construction (AEC) industry has been using two dimensional (2D) drawings for design, and communication, however, useful information is lost during handover of a project life cycle (Sacks et al, 2018). Profuse number of software tools are used for various tasks in a construction project but few of these have support of data exchange between each other, resulting in data loss during data exchange or requires a manual entry of data which is laborious, time consuming, and inclined to errors (Borrmann et al, 2018). According to Gallaher et al. (2004), interoperability problems in the U.S. capital facility led to a \$15.8 billion annual cost in 2002, which stem from extremely fragmented nature of the AEC industry.

The construction industry is governed by a wide range of codes and guidelines that specify the technical and standard requirements but these functions are iterative and include incompetent and costly manual processes (Preidel et al, 2018). Manual quantity take-offs (QTO) are conducted in various phases of construction which are subject to errors due to change in design and variations, therefore, make it protracted (Mattern et al, 2018). The industry suffers from high variability, low performance, and risky working environment (Ballard and Howell, 1994; Diekmann et al, 2003). 2D-based design conducts critical assessments such as cost estimates, energy analysis, structural details after the design is complete, which is too late and of high cost (Eastman et al, 2008). Sacks et al. (2018) state that from 1967-2012, the manufacturing productivity is more than doubled, while productivity for construction industry is almost remained constant (U.S. Census Bureau, 2016a).

The construction industry is a wasteful industry. A meta-analysis of construction between 1970 to 2000 by Horman and Kenley (2005) reported that almost 49.6% of construction workers spent on non-value adding activities. Excess consumption of materials (Formoso et al, 2002), defects (Josephson and Hammarlund, 1999), rework (Hwang et al, 2009), work-in-progress (Yu et al, 2009), indirect work (Kalsaas et al, 2014), and unproductive time (Horman and Kenley, 2005) are designated as wastes.

With the emergence of lean concepts, wastes are all those activities that consume resources, take time and space but do not add value (Womack et al, 1997). Seven wastes are identified by Ohno (1988) which are: i) overproduction, (ii) waiting, (iii) transportation, (iv) over-processing, (v) inventory, (vi) movement, and (vii) defects. Top wastes in the construction industry are: (i) making-do, (ii) work-in-progress; (iii) unfinished work; (iv) transportation; and (v) defects.

Digitalisation has revolutionised other industries, prompting formidable increase in productivity, product quality and cost reduction, nonetheless, the AEC industry falls way behind other industries in adoption of digitalisation (Borrmann et al, 2018). The construction industry is eminently different from other industries, particularly these distinctions consist of on-site production, uniqueness and complexity (Alarcón, 1997; Koskela 1992). Moreover, finished goods can be moved to other geographical locations for consumers while construction products cannot be moved (Salem et al, 2006).

To address and cope with abovementioned problems, there have been attempts for new approaches. Among them, Building Information Modelling (BIM) as a transformative information technology and lean construction (LC) as a management approach are of significant importance in the AEC industry.

BIM, an invaluable modelling technology, allows a precise digital model of a facility which can support all phases of construction through all geometric and non-geometric data required for design, construction, procurement and operation (Eastman et al, 2008). BIM tackles the information loss during handover of documents between the phases of the building life cycle, therefore, it improves the flow of information among the stakeholders compared to traditional paper-based information exchange (Borrmann et al, 2018). The segmented nature of the AEC industry demands huge exchange of information, but software packages present in the market do not support or rarely support exchange of data (De Gaetani et al, 2020). This problem is solved by a standardised file exchange format which is called Industry Foundation Classes (IFC), developed by buildingSMART (Sacks et al, 2018).

Another paradigm shift in the management science is the lean concept which is considered one of the most influential ideas (Buchanan and Huczynski, 2019). Lean production supersedes craft and mass production, and it is the production of what

customers want in no time and with no inventory (Tommelein, 2015). The core problem in the AEC industry is that the value generation dispersed across various disciplines, such as architectural, engineering, consultancies, and construction firms (Borrmann et al, 2020). Firms in the AEC industry cooperate on an ad hoc basis which its temporary nature impedes coordination and collaboration.

BIM and LC concepts are independent and separate, however, there seems to be great synergies between the two (Sacks, 2010), and can support the entire building lifecycle from design to facility management (Dave et al, 2011). Lean thinking and specifically Last Planner® System (Ballard, 2000) arose due to poor field production management, on the other hand, BIM emerged in response to the failure of drawings for communicating product information (Dave and Sacks, 2020). Gerber et al. (2010) found that BIM and LC had positive interactions without prior intention for the integration of the two.

1.1 Statement of the Problem

Architecture, engineering, and construction (AEC) industry falls far behind other industries in adopting technological innovation and digitalisation. Current push for innovation and productivity drives the AEC industry for digitalisation and technology. The built environment is a project-based production which involves various disciplines that each creates information. The segmented nature of the AEC industry makes the information management an arduous task. The AEC industry comprises of complex undertaking that requires close collaboration and loss-free exchange of information among the stakeholders. Productivity and product quality are relatively low compared to other industries. Invaluable information is lost during the building life cycle when information is handed over to other disciplines (e.g., subcontractors and mechanical, electrical and plumbing (MEP)) and phases such as design, construction and operation. Labour intensive efforts are spent on recreation of data and they are prone to errors. In the traditional construction processes, drawings are checked manually, which result in significant errors.

On the other side, as one of the wasteful industries, material losses are traditionally regarded as the main source of waste in the construction industry. Recently, with the emergence of lean concepts, waste is considered as activities that consume resources, take time and space but do not add value. Seven wastes are identified by Ohno (1988)

which are: i) overproduction, (ii) waiting, (iii) transportation, (iv) over-processing, (v) inventory, (vi) movement, and (vii) defects. Top wastes in construction industry are: (i) making-do, (ii) work-in-progress; (iii) unfinished work; (iv) transportation; and (v) defects.

Traditional handover of drawings as printed papers or limited digital format is the source of many information losses during entire project life cycle, especially from one phase to another phases (design, construction, and operation) (Borrmann et al, 2020). Another problem with 2D design is that critical analysis such as cost estimates, and energy analysis are done last with substantial cost and time at last which is too late to bring changes (Sacks et al, 2018). For example, when clients are not provided with complete drawings for the operation, they will create their own drawings, which is both time consuming, and drawings and data may vary from original.

The core problem in AEC industry is that value generation dispersed across various disciplines, such as architectural, engineering, consultancies, and construction firms (Borrmann et al, 2020). Firms cooperate on an ad hoc basis which its temporary nature impede coordination and collaboration.

1.2 Purpose of the Thesis

This thesis aims to study integration of BIM and lean construction. Lean construction as a management philosophy aims to minimize information losses, and other wastes; maximize value from customer's perspective. Lean construction is perceived as a substantial concept in improving quality, productivity and intended value to the customer. Industries have used waste removal as a significant driver for efficiency improvement. Therefore, there are information loss because information is submitted in physical printed plots.

Moreover, construction industry is of crucial waste due to inefficient processes. Here building information modelling comes into play as new method for use to technology in design, construction, and operation of built facility. Contrary to store of information in drawings, BIM use building information models for storage, and exchange of information (Borrmann A., et al., 2020). BIM aims to contribute to efficient storage, exchange, and use of information created by all disciplines. Furthermore, BIM support

collaboration among stakeholders which is the achilles' heel of AEC industry due to its segmentation, and temporary nature of collaboration.

BIM and LC are two independent approaches that can be embraced separately but there seems to be synergies between the two (Sacks et al., 2010). Sacks et al., (2010) identified 56 interactions that 52 of them show positive interaction. BIM approach, by visualisation of synchronized models architectural, structural, and MEP enables clients and users to add their perspectives for value generation. Moreover, it allows designers to understand the clients' requirements. Clash detection by BIM delivers a clash free model by aligning all disciplines model together, thus save enough time and costs.

Therefore, this thesis will study:

- What are BIM functionalities?
- What are lean construction principles?
- How do these principles and functionalities contribute and support each other?



2. LITERATURE REVIEW

2.1 Building Information Modelling

The AEC industry has fallen behind in adoption of technology compared to the other industries. BIM, as a promising technology, is a paradigm shift in the industry. The following sections describe what BIM is and its benefits. There is an increasing complexity in construction projects and lack of coordination among the stakeholders, such as architects, engineers, contractors, suppliers, regulatory authorities, financiers (Sears et al, 2008). Low quality, time and cost overruns, and considerable overuse of the resources arise due to the convoluted nature of the construction projects (Kerosuo, 2015). According to a report by World Economic Forum, the productivity in the construction industry has dropped about 20%, while the productivity on non-farm business increased over 150% (World Economic Forum, 2016). The AEC has long quested to find a way to reduce project duration and cost, increase productivity, and meet the clients' demands (Azhar, 2011). BIM provides pertinent information (spatial relationships, geometry, cost estimation, schedule, and materials) to all stakeholders for effective collaboration throughout the whole life cycle of the project (Azhar, 2011). Currently, BIM is considered as a seminal approach for digitisation of the construction industry and pave the way for future adoption of technologies (Oesterreich and Teuteberg, 2019).

Smith (2007) has defined BIM as a “digital representation of the physical and functional characteristics of a facility”. This definition indicates that BIM aims to build a facility virtually, before the physical construction of the building, so by simulation problems are detected, analysed, and resolved. The BIM handbook (Sacks et al., 2018) defines BIM as “BIM as a modeling technology and associated set of processes to produce, communicate, and analyze building models”. The building model in this definition is digital representations of building elements, which can be recognized by BIM software applications; in addition, the parametric design gives the flexibility for intelligent manipulation. There are data, which determine the behaviour of building model, which is required for quantity takeoff, specification and functional analysis

(structural, thermal, acoustic, safety). BIM has been defined as “a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building’s life-cycle” (Succar, 2009).

The National BIM Standard-United States (NBIMS-US) initiative categorises BIM into three ways:

- as a product
- as an IT-enabled, open standards-based deliverable, and a collaborative process
- as a facility life cycle management requirement.

Bryde et al. (2013) state that BIM is not only a software for 3D modeling of objects but indicates project management tools. BIM supports collaboration, reducing project documentation and increasing the project outcomes (Bryde et al, 2013). Form, function and behaviour of building information model differentiate BIM from 3D models (Tolman, 1999). Building information modeling as a simulation technology helps stakeholders visualise a digital building model and detects design, construction, functioning and maintenance errors beforehand, and workflow aspect of BIM facilitates collaboration and integration of AEC disciplines and stakeholders (Nawari, 2018). BIM functionalities include interoperability, clash detection, construction scheduling, collaboration and communication and 4D scheduling (Sacks et al, 2010; Cao et al, 2019). BIM enables safety assessment, site logistic planning, activity sequencing, and progress tracking (Bryde et al, 2013). Building information model can be used for code checking, clash detection, forensic analysis (Potential failures, leaks, evacuation plans) and facility management (Azhar, 2011). Information stored in the BIM database are utilised for space planning, facility maintenance and refurbishment during operation phase (Becerik-Gerber et al, 2012; Cao et al., 2019).

In the last decade, regulatory authorities initiated BIM standards and policies in the US, the UK, Finland, Singapore, Australia, and Norway (Yilmaz et al, 2019). The first BIM software in 2000 marked the popularity of the new approach in the AEC industry (Merschbrock, 2014). The emergence of new frameworks, such as Integrated Project Delivery (IPD), which demands collaborations among stakeholders, accelerated the needs for BIM applications (Sacks et al, 2018). BIM aims to deliver collaboration and

communication by a virtual model, which its benefits outpace the traditional paper-based tools.

Major characteristic of BIM is well structured generation and exchange of information among the multiple participants. ISO 19650-1 2018 provides us with an international standard for managing, exchanging, and recording of created information by BIM. BIM delivers broad spectrum of benefits to the AEC industry, ranges from feasibility analysis to operation and finally dismantling of the facility. Azhar (2011) declares the benefits of BIM as (i) accelerating the design and build process; (ii) effortless sharing and reuse of data; (iii) improved designs via continuous assessment; (iv) precise forecast of environmental and life-cycle data; (v) enhanced production quality; (vi) customers' satisfaction, via better visualisation; and (vii) use of the repository for facility management. In the following sections, the most common advantages of BIM are summarised in each stage of the construction project.

2.1.1 Pre-construction and design development stage

BIM model helps owner to justify economically the facility early before design, ensures the facility for demanded purposes, and supports collaboration by developing the model through the life cycle of the project (Sacks et al, 2018). Large number of benefits are provided by BIM during the design stage of a construction project. Myriad of stakeholders in the AEC industry with contradicting interests requires a good approach for exchange and creation of information, thus, BIM is assumed to deliver such characteristics (Scheffer et al, 2020). Availability of authentic and up-to-date information ensures optimal decisions from set of available alternatives. BIM-based construction networks improve coordination among stakeholders (Cao et al, 2017). Digital building information models provide real time information required for different parties that highly support collaboration and allow automatic inconsistencies verification (Schapke et al, 2020). Data management of digital construction and seamless exchange of these data during various stages of construction require a good data management system. Common Data Environment (CDE) facilitates an effective and precise share of various information for all parties (Richards, 2010). He also states that CDE impedes redundant information and ensures updated information to all parties.

Accountability reason does not appreciate a single shared model from traditionally practical point of view (Pareidel et al, 2020). They, therefore, state that a domain specific approach is adopted in a way that each author can create information in his or her sub-model. Data management of digital construction and exchange of these data during various phase of construction requires a good data management system.

During the project design, planning, construction and operations colossal amount of data exchange happens; specifically, digital building data are handed to other disciplines and finally handed to client (Borrmann et al, 2020). Multitude of disciplines involved in a project are using different commercial software tools for different purposes such as structural analysis, energy analysis, cost estimation, and facility management (Shoieb et al, 2020) and these segmented disciplines use applications, which rarely support streamline of information flow among them. Therefore, existing data are re-created for various analysis which is laborious and inefficient. For this intent, a loss-free exchange of data format is required to support exchange of both semantic and geometric information for interoperability (Venugopal et al, 2012). Industry foundation classes (IFC) is developed for standardised data format to facilitate a vendor neutral exchange of digital building models.

Lack of collaboration among design teams is the main reason of clashes (hard clashes, soft clashes or process clashes) or spatial conflicts. Therefore, a cross-disciplinary collaboration facilitated by BIM can reduce these clashes (Akponeware and Adamu, 2017). BIM-enabled automatic clash detection is used for design coordination (Cao et al, 2015). In the design phase, clash detection, improved design, simulations, design authoring and code checking, and cost estimation enumerated as BIM benefits (Gu and London, 2010; Sacks et al, 2018; Cao et al, 2019). Lean approaches fight for waste and endeavour for perfection (Tommelein and Gholami, 2012).

The construction industry is governed by guidelines that ensure specifications, and requirements to be met. Since these are mostly iterative and manual approaches, digital methods in the AEC industry especially BIM aims to automate these time-consuming and error prone processes (Cornelius and Borrmann, 2020). Models to be checked for code compliance, hence designer, contractor, client and other disciplines should be able to interoperate (Nawari, 2018), therefore IFC plays a key role in automatic compliance code checking. Eastman et al. (2009a) state that for automation of code checking, code should be translated into machine-readable language and then the

model can be executed for compliance with the codes. Cornelius and Borrmann (2020) explain the availability of both geometric and semantic information as valuable for compliance code checking yet translation of these guidelines are difficult task since some of the requirements are contextual. The IFC open data model has facilitated and enabled emergence of various tools for compliance code checking, namely Express Data Manager (EDM), Solibri Model Checker (SMC), among others (Dimyadi and Amor, 2013).

Manual pricing and costing of construction projects are a challenging task from unstructured blueprints and usually prone to errors and time consuming (Mattern et al, 2020), as well as susceptible to errors due to antiquated information or design changes. Conventional cost estimation done from quantity take-off should be done continuously as the design changes, which makes it laborious task. BIM-based quantity take-off and cost estimation from continuous updated data will give precise cost, thus a successful project that is within the budget (Abanda et al, 2017). BIM-based quantity take-off ensures bill of quantities (BoQs) based on most recent data, access to broad range of data, and finally ensure prevention of data loss due to central model data structure. (Mattern et al, 2020).

The parametric design and its application are the foundation of many BIM's functionalities (Sacks et al, 2004). The parametric design maintains all design in a single integrated source and any change is reflected to all other views automatically. A single source can maintain the consistency for drawings, BoQ and any other document. The single source generates the exact documents such as plans, elevations, sections, details and reports (Sacks et al, 2004). Mollasalehi et al. (2016) expressed benefits of BIM as greater value generation and smoother workflow. Moreover, 3D visualisation in the early design phase provides the client with a vivid image of proposed potential facility (Mollasalehi et al, 2016). Quantity take-off, accurate cost estimation and BoQs are offered by BIM functionalities (Raphael and Priyanka, 2014). BIM delivers a rapid process, quality design, better customer service, and life cycle data (CRC Construction Innovation, 2007).

2.1.2 Construction stage

After the design phase, the building information models are handed over to contractor for the construction phase. Immediately after design completion, the BIM model is

used for tendering, which determines the customer requirements and tender price (Borrmann et al, 2018). BIM provides with a feature that enables automatic, up-to-date, and consistent when there is a change extraction of BoQs through 5D (Azhar, 2011). 4D modelling helps visual communication among the project teams, increases accurate work plans, site planning and associates each building parts to schedule (Konyushkov et al, 2020). According to Borrmann et al. (2018), BIM models avoid spatial and time conflicts between building components during the construction phase, enable cost control during construction and invoicing.

Successful project management requires accurate site information; however, up-to-date data collection of construction site needs considerable amount of endeavour and cost (Kim et al, 2020). BIM is used for construction work progress monitoring in which time dimension is correlated with 3D model. As-planned building model in 3D is superimposed with as planned schedule, which the result includes a thorough construction process (Braun et al, 2018) by laser scanning and photogrammetric -used for as-built point clouds, and then compared with as planned model.

The construction industry is among the riskiest industry and designated as top on work-related injuries and fatalities rate (Teizer and Melzner 2018). These hazards include falling from height (Huang and Hinze, 2003), electrocutions, struck-by-object, and caught in between (OSHA, 2018). BIM is used for automated fall risk diagnose by rule checking (Choe and Leite, 2017), analysis of risk associated with scaffolding (Kim et al., 2016), provides visualisation by use of remote sensing and enables workplace modelling (Zhang et al, 2015), create safety knowledge for future projects and facilitates easier job hazard analysis (Zhang et al, 2015).

2.1.3 Operation stage

Facility operation and management demands concise and solid data (Atkin and Brooks, 2015). Data created during the planning, design and construction stages are of significant importance for handover of the built assets (Love et al, 2015). The owner can realise considerable advantages of BIM by using its model during facility management. Building owners use building information models for improving building performance, generating value for the customer and support lean construction practice, optimising facility management and maintenance through pro forma

analyses, operation simulations, commissioning and asset management, and building upgrades (Sacks et al, 2018).

2.2 Lean Construction

Lean concept emerged after the book titled “The Machine that Changed the World” by Womack et al. (1991). It introduces a new production philosophy; namely Toyota Production System (TPS), which supersedes mass production. Ideally, lean production is the delivery of products to customer just-in-time and without any inventory (Tommelein, 2015). According to Womack and Jones (1997), the five principles underlie lean thinking are: value, value stream, flow, pull and perfection. They emphasise that value is determined by customer, set of actions should be mapped which end up to value, these values creating actions processes should flow, customers should be allowed to pull value from enterprise, and finally the target should be set for perfection- an endless eagerness for improvement.

The construction industry suffers from low productivity and quality, and poor working conditions and safety (Koskela, 1992). To this end, lean construction indicates the application of lean principles and lean thinking to the AEC industry (Tommelein, 2015). Lean construction aims to deliver improved value through waste reduction and continuous improvement by making the processes flow (Sacks et al, 2018). The term “lean construction” was used first by International Group for Lean Construction (IGLC) when they met in 1993.

Lean production core concepts are just-in-time (JIT), total quality management (TQM), time-based competition, and concurrent engineering (Koskela, 1997). JIT addresses waiting time elimination, TQM emphasises the elimination of rework. Both, JIT and TQM aim smooth flow of work, material and information (Koskela, 1997). Koskela (1992a), listed the lean principles at: reducing non-value-adding activities, increasing value through pull flow, reducing variability, reducing cycle times, simplifying the process, increasing flexibility, increasing transparency, entire process control, adopting continuous improvement, standardizing, and balancing flow and transformation improvement.

However, there are substantial differences between lean construction and lean production. The construction industry is one-of-a-kind, on-site production, temporary

endeavour Koskela (2000). Koskela (2020) states that lean emerged in the construction industry due to the construction's chronic problems for decades. He states that lean construction is a combination of contextual problem-solving methods in the industry and generic lean principles adopted from TPS manufacturing. So, the question arises: Can lean principles, methods and tools directly be applied from manufacturing to construction?

To internalise the lean concepts in the AEC industry, we need to understand its theory. Koskela (2000) explains lean as developing theoretical concept of production to two new theories namely the flow theory and value generation theory. Fujimoto (2012) sets forth Toyota Production System (TPS) as set of unrelated and organizational routine indicating no underlying theory. Koskela (2020) emphasises that the lean idea has superseded the production theory. In the first place, therefore, we should understand the production theory.

2.2.1 Waste in construction

Lean uses waste elimination as significant drivers for improvement of efficiency (Ohno, 1988), and by working harder it improves the efficiency of each activity (Koskela, 1992). Generally, waste is understood as material loss indicating only construction debris to be removed from construction sites (Bossink and Brouwers, 1996). In the lean concept, waste is non-value adding activities that utilise resources i.e., activities that take time, resources and space but do not add value to the products from customer perspective (Koskela, 1992). Initially, waste has been studied from two perspectives: first, when resources are used but create products that cannot be sold and second, it is a waste of time not using resources (e.g., energy, labour) for all humanity (Koskela et al, 2012).

The most famous taxonomy of waste is given by Ohno (1988): overproduction, waiting, transportation, over-processing, inventory, movement, and defects products as critical wastes for TPS. He emphasises overproduction as root and substantial waste. Ohno does not follow any ultimate definition of waste but targets the key concept of waste lead to different types of waste (Bølviken and Koskela, 2016).

Bølviken et al, (2014) listed three types of waste in compliance with TFCV theory of production. These wastes are material waste, time loss and value loss. Material loss is associated with transformation, time loss is related to flow, and value loss is associated

to value perspective. The definition of waste and value are defined as (Bølviken et al, 2014): value is a wanted output and waste is the use of more than needed, or an unwanted output. They state that value indicates functionality, utility and benefits of a product and lean adopts a holistic approach which focuses on the final goal; therefore, value is defined from the customer's perspective. Formoso et al. (2020) categorise the construction waste as (i) making do, (ii) work-in-progress; (iii) unfinished work; (iv) transportation; and (v) quality deviations.

Making-do as a start or continuation of task when needed inputs are not available, expounds that people will improvise in critical situations or divert from objective in compliance with available resources (Cunha, 2007). Consequences of making-do is to stop execution of the task or continue even some prerequisite is lacking (Formoso et al, 2020). They state that the first one will lead to waiting which is another type of waste Patton (2013), and second one will lead to either total stoppage or low-quality product or increase share of work-in-progress (Koskela, 2004). Making-do waste is fundamental waste that will lead to other waste such as material waste (Formoso et al, 2020).

Work-in-progress (WIP) is unfinished products or partially finished works that needs further processes (Hopp and Spearman, 2011). This is the type of inventory of unfinished or intermediate product, which hides problems regarding quality, transportation and moving (Ohno, 1988). Studies enumerate causes of work-in-progress in construction sites as existence of huge batches (Koskela, 1992), making-do (Formoso et al, 2017), inadequacy of synergies among workers (Bashford et al, 2003). Unfinished work is a type of waste that workers leave minor tasks undone when leaving the construction sites (Fireman et al, 2013). Unfinished work results in twist in the percent plan completed (PPC) metric for the Last Planner System (Ballard and Howell, 1998) users. Minuscule work packages are considered done in the schedule while it is left in the operational plans (Formoso et al, 2020). These minor unfinished work packages typically contribute to non-value adding activities such as movement, set-up and cleaning (Fireman et al, 2013). These small unfinished tasks lead to making-do and hinder quality control (Formoso et al, 2020).

Ohno (1988) describes transportation waste as transference of materials that incurs cost but adds no value. Materials, equipment, and labour are wasted during transportations (Formoso et. al, 2002). Pérez and Costa (2018) pointed out the main

causes of transportation waste as difficulties in access road, insufficient stockpile of materials, improper equipment, and unskilled labour. Formoso et al. (2002) state that transportation waste constitutes major portion of waste in construction.

Defects or quality discrepancy is a broad concept that cannot be measured by numbers (Hopp and Spearman, 2000). Defects come from poor knowledge, deficient information, and carelessness (Josephson et al, 1999). In a case study by Josephson et al. (1999), defects costed approximately 6% of the production cost. Hammarlund et al. (1989) pointed out that defects originate from production, site management, and workmanship with the percentages of 54%, 34%, and 20% respectively. Quality is defined from product perspectives (e.g., conformance, reliability, performance), illustrating that quality is finally perceived by client (Garvin, 1987).

2.2.2 TVF theory of production

Koskela (1992) introduced a new production philosophy into the construction industry namely, Transformation-Flow-Value (TFV). He insisted that all these three are of significant importance to an efficient production system.

2.2.2.1 Transformation

According to Holweg et al. (2018), transformation is the base of the production theory, namely conversion of inputs into outputs. Transformation perspective of production turns raw materials into products through the application of labour, machinery and energy (Bølviken et al, 2014). Transformation remained dominant as production theory throughout the 20th century. Koskela (2000) states that transformation perspective omits two other perspectives (flow and value).

2.2.2.2 Flow

In second perspective, production is viewed as flow, in which the flow is both in time and space (Koskela, 2000). Flow indicates the process through which product are transformed from inputs to output should flow (Womack and Jones, 1997). They also state that customers pay for rework and waiting but do not add value to the customers.

2.2.2.3 Value

The first two perspectives are internal and concentrate on the product processes, while the third perspective is an external focus on the customer requirements, namely value

(Bølviken et al, 2014). Value generation is the core pillar of lean design. The customer requirements in the light of design specifications are used as inputs for the design process (Ballard and Koskela, 1998). Traditionally, a linear process was adopted in alignment with predefined numbers of requirements but in the lean approach, value is captured by understanding the customer's need and translating it to products with consideration of minimum costs and time (Tzortzopoulos et al, 2020). Integration of lean and BIM helps realisation of value generation throughout the facility life cycle (Dave et al, 2013).

In 1990s, globalisation and severe competition in the manufacturing industry demanded rapid responses to customer's need and its translation to the product (Kagioglou et al., 1998). Lean design is the tool for generation of value and reduction of information waste (Tzortzopoulos et al, 2020). They also state that lean design transforms information, and adds value to it in collaboration with clients just same as production processes. Challenges such as difficulty in capturing customer's needs, balancing between competing requirements, and formation of a project-based team are among construction project barriers (Tzortzopoulos et al, 2020). New Product Development (NPD) starts with recognition of market opportunity, concept development, product design, market launch, taking the feedbacks from the customer and translation/inclusion of these requirements into the product (Cooper et al, 1998). Therefore, in the NPD, there is both product and production process design. Tzortzopoulos (2004) defines the product development process as "the set of activities needed for the conception and design of a built product, from the identification of a market opportunity to its delivery to the client". This definition not only includes design phase but also processes during the production. Wang et al. (2011) defines NPD as "the application of lean principles to the product development process to eliminate the waste". This definition indicates that there is waste in the design phase, and application of lean principles can minimise or remove these wastes. Process models adopted from manufacturing industry, should display details of activities, relationships among these activities, inputs, outputs and information flows, roles and interest of stakeholders (Kagioglou et al, 2000). Lean product development aims to reduce protracted development times, tremendous costs of development, production cost and finding innovative solutions (Ward and Sobek, 2014). Lean sees design phase as production process (Ballard and Koskela, 1998). Therefore, in lean construction,

Koskela's Transformation-Flow-Value theory is used: Transformation is the conversion of inputs into outputs, flow is that information should be disseminating across activities and stakeholders, finally the value generation is addition of value to the product for customer's expected use. Realisation of design as flow of information reduces waiting time for information, inspection of design, and revision of design according to the specifications (Ballard and Koskela, 1998). Designing for value meeting customer's needs are done by pulling the information from them and translating to the products (Koskela, 2000).

Segmentation in the construction industry leads to poor coordination, modest communication and excessive variation (Kagioglou et al., 2000). Design managers belittle the importance of people, production processes, environment, and technology (Koskela et al, 2002), but fixate on projects, tasks, resources and contracts (Howell, Windahl, and Seidel, 2010). The main problems in the design phase are poor communication and coordination among the stakeholders (Koskela et al, 1997), lack of integration and shared understanding between the design teams (Whelton and Ballard, 2002), difficulties in pulling customer's need and conversion to the products (Ballard and Koskela, 1998), insufficient time for understanding the customer's need (Lima et al., 2009), difficulties in trading off between competing needs (Ballard and Koskela, 1998). Furthermore, the design issues associated with the processes are last minute recognition of errors and rework (Ballard and Koskela, 1998), inability in finding non-value adding activities (Ballard and Koskela, 1998), deficient and missing information (Koskela et al, 1997), poor planning and control at early design phase (Ballard and Koskela, 1998), and poor adaptation of design flows (Tauriainen et al, 2016).

2.2.3 Tool and techniques for TVF theory of production

To alleviate and minimize the waste mentioned above, some tools and techniques are utilised. Koskela (2000) suggests that the TFF theory aims to mitigate making-do waste and the flow perspective targets minimizing variability. In the following sections some tools are suggested for the TFF theory application.

2.2.3.1 Last Planner System™

The Last Planner System™ (LPS) developed by Ballard, is a method for on-site production planning and control (Ballard, 2000). Project control is the alignment of

cost and schedule to the project scope, and production control direct toward this target in the production level (Ballard and Tommelein, 2016). The LPS controls production for the achievement of the set objectives for the general project (Ballard and Tommelein, 2016). The chronically low workflow in the construction industry was behind the LPS (Ballard, 2000).

Koskela, Howell, and Ballard noticed that around 54% of construction plan failed (Ballard and Howell, 1998), and this indicates that traditional project management methods (Work Breakdown Structure, Critical Path Method, Earned Value Analysis, etc.) cannot deliver the project on time, within the budget, and at desired quality (Ballard and Howell, 2003). Koskela (2000) suggested that adopting the Toyota Production System may solve this construction problem, which he named lean construction. Lean construction is the application of the LPS.

The conventional project scheduling does not address long-term planning and short-term execution planning since the work package is not planned in detail and constraints are not removed before the execution (Heigermoser et al, 2019). Therefore, the LPS is developed to ensure the smooth workflow and enable lookahead planning (Hamzeh et al, 2008)

The lookahead planning, as a weekly-base planning which identifies the task's constraints, assigns rules, discusses workflow and prepares all necessary resources for the execution, connects the gap between master schedule and short-term execution plan of work (Heigermoser et al, 2019).

Ballard et al. (2002) explain that traditionally, planning is a top-down approach in which the head office dictates what to be done while in a lean project, by utilisation of LPS, the subcontractors or anyone in charge of real work on site participate in planning of work packages to be carried out. Foreman, site engineer, shop foreman, or whoever in charge of short-term tasks are involved in the short-term planning.

Production control with Last Planner System (Figure 2.1) is conducted as follows (Ballard et al, 2002):

- Brings the activities from phase schedule into a 6-week lookahead, evaluates for potential constraints, and proceeds only if those constraints are expelled.
- PPC metrics are traced during each planned period and defect assignments are tracked back to its origin.

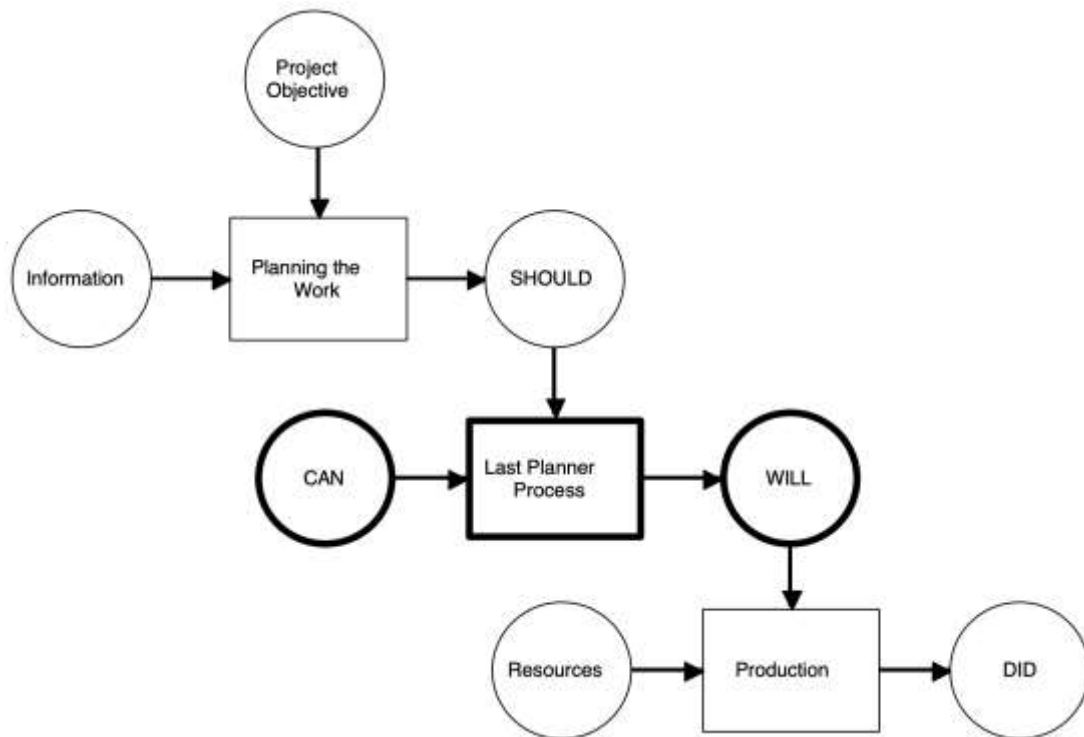


Figure 2.1: The last planner system (Ballard, 2000).

Lookahead planning ensures availability of sufficient mature tasks for each week and determine how, by whom, and what work should be done (Ballard and Tommelein, 2016). Ballard (1997) states that lookahead serves the following functions:

- Shape workflow sequence and rate,
- Match workflow and capacity,
- Decompose master schedule activities into work packages and operations,
- Develop detailed methods for executing work,
- Maintain a backlog of ready work,
- Update and revise higher level schedules as needed.

Some techniques used during lookahead planning are constraints analysis and pull planning.

Tasks in a 6-week lookahead planning are subjected to constraints analysis. Constraints are either physical (such as availability of plotter) or informational (e.g., soils report prior to foundation design and engineering details) (Ballard and Tommelein, 2016). These constraints are contract, prerequisite work, design, space, equipment submittals, materials, and labour whereas other constraints that may cause

work blockage, are permits, inspections, approvals and any other category of constraints (Ballard, 2000). The key point is not allowing tasks to production schedule if the constraints cannot be removed in time.

Pull planning is the introduction of materials and information into the production process; an alternative for traditionally practiced push planning dictates inputs into process based on completion date (Ballard, 2000).

Traditionally, the construction planning was pulled by manager to the foreman and workers without considering the physical and informational constraints. The LPS divides the tasks into four types: the work that needs to be done according to the progress (Should); the actual work that can be done because of the project constraints (Can); the work promised to finish after evaluating all constraints (Will); and the work already done (Did) (Ballard and Tommelein, 2016).

2.2.3.2 Visual management and other lean tools

Lean construction uses various tools and techniques ranging from Andon, Kanban and 5S. Most of these tools help visual management that facilitates fast and solid means of communication. Visual management has been the integral part of Toyota Production System and its by-product namely lean production.

Tezel (2011) states that visual management has been increasing in construction and aims to make coordination and communication simpler and more efficient. Visualisation excels other forms of communication in which the images can be perceived in 13 milliseconds (Lewis, 2014), whereas a normal reader can read 200-300 words per minutes (Koskela et al, 2018). Visual management, therefore, enables easier and fast communication compared to the other forms of communications such as written or oral.

Visual management consists of information giving, signalling and mistake-proofing/ Poka-Yoke (Shingo, 1989). Visual management serves various functions which include:

- Transparency: “The ability of a production process (or its parts) to communicate with people” (Formoso et al, 2002).
- Discipline: “Making a habit of properly maintaining correct procedures” (Hirano, 1995).

- Continuous Improvement: “An organization-wide process of focused and sustained incremental innovation” (Bessant and Francis, 1999).
- Job Facilitation: “Conscious attempt to physically and/or mentally ease people’s efforts on routine, already known tasks by offering various visual aids” (Tezel et al, 2009).
- On-the-Job Training: “Learning from experience” (Mincer, 1962) or “Integrating working with learning” (Sumner et al, 1999).
- Creating Shared Ownership: “A feeling of possessiveness and being psychologically tied to an object (material or immaterial)” (Pierce et al, 2001).
- Management by Facts: “Use of facts and data based on statistics” (Gunasekaran et al, 1998).
- Simplification: “Constant efforts on monitoring, processing, visualizing and distributing system wide information for individuals and teams” (Tezel et al, 2009).
- Unification: “Partly removing the four main boundaries (vertical, horizontal, external and geographic) and creating empathy within an organisation through effective information sharing” (Tezel et al, 2009).

Ohno (1998) explains Andon as a visual control where the device updates the current status of the production and gives signal for the emerging problems and gives alert that where and when the problem has occurred at a glance; and Kanban as a scheduling system where it shows what to produce, when to produce and finally how much to produce. Kanban is a Japanese term for cards used for pull flow on lean tool and closely related to JIT. It removes overproduction and as a result there is no need for inventory and warehouse.

5S lean tool is used for well organized, uncluttered, safe and clean workplace. 5S exposes hidden problems and ensures smooth workflow (Hirano, 1995). Visual control improves value by providing a good communication medium and tell if the value deviates from standard (Liker, 2004). 5S consists of ranges of activities that aim to eliminate wastes that are reasons for defects, errors and unsafe workplace. These are Seiri, Seiton, Seiso, Seiketsu, and Shitsuke, and translated into English as (Liker, 2003):

- Sort: Sort through items and keep only what is needed while getting rid of what is not.
- Straighten (orderliness): A place for everything and everything in its place.
- Shine (cleanliness): The cleaning process often acts as a form of inspection that exposes abnormal and pre-failure conditions that could hurt quality or cause machine failure.
- Standardise (create rules): Develop systems and procedures to maintain and monitor the first three Ss.
- Sustain (self-discipline): Maintaining a stabilised workplace is an ongoing process of continuous improvement.

Visual control is an important aspect of visual management which is facilitated by KanBIM. The KanBIM™ system is a lean tool developed for workflow control on construction sites and short-term work planning and controlling by visualisation of work under way (Sacks et al, 2011). ‘KanBIM’ (Kanban using BIM), is incorporation of lean principles and BIM technology. The term ‘Kanban’ is a Japanese term for cards or signs, which is used for pull flow control (Liker, 2003). Kanban ensures pulling material on just-in-time basis and pull flow is to produce what is needed, when it is needed and how much it is needed (Arbulu et al, 2003), and tries to eliminate over production and increase flexibility. Kanban is implemented for heavy civil projects (Jang and Kim, 2007) and supply of materials (Arbulu et al, 2003).

2.2.4 Summary of lean construction

The construction industry is considered of immense wastes, which can be associated with ‘T’ view of production. Lean construction introduces and utilizes ‘TFV’ production view which deploys the techniques and tools that aim minimising the construction wastes.

The Last Planner® System is one the famous tools for dealing with some of the complications, which were discussed in the previous chapter. The LPS improves the flow of work and reduces variability. The LPS challenges traditionally practiced critical path method (CPM). In CPM, the plans are forecasts and the forecasts are uncertain and especially these forecasts are made for long period and high level of details. Lookahead planning allows LPS for constraints removal and ensures smooth

workflow. Moreover, CPM assigns tasks without considering the capacity of workers while lean construction and LPS pull flow.

2.3 BIM and Lean Interaction

As different and impendent approaches, lean construction and BIM both deal with the complexity, unproductivity and wasteful nature of the AEC industry. They can be adopted and implemented independently, however, the full potential of both can be achieved by integrating them. 56 interactions (Sacks et al, 2010) by juxtaposition of BIM functionalities and LC principles, show positive interactions except four of them. In an attempt for integration of LC processes and BIM, Khanzode et al. (2006) struggled to provide a conceptual framework to relate virtual design and construction with lean project delivery processes. In their over four-year span of time case study, Rischmoller et al. (2006) concluded that the realisation of computer advanced visualisation tools (CAVT) lead to waste reduction, enhanced flow and better customer value, which demonstrate substantial synergy between lean construction and CAVT. Sacks et al. (2018) declare that BIM fulfills some of lean construction principles and highly ease fulfillment of other lean principles. The most significant synergies are: BIM reduces variation, shortens cycle time, improves information flows and finally enables product and process visualisation, simulation and analysis.

Sacks et al. (2010) have put together some BIM functionalities (Table 2.1) with lean principles (Table 2.2) in a matrix. They suggest this study as a framework for further studies for validation of the interactions. Figure 2.2 demonstrates the interaction matrix provided by them based on the literature.

Table 2.1 : BIM functionalities (Sacks et al, 2010).

Design	BIM Functionality	Descriptions	Source
	Visualization of form 1. Aesthetic and functional evaluation	BIM provides all non-technical stakeholders with real time visualisations to communicate and cooperate information and keep consistencies. Visualisation of forms allow various disciplines to deal with multiple tasks more easily such as cost estimation, energy analysis, and production planning.	(Mill et al, 2013; Sacks et al, 2010) (Johansson et al, 2015)
	Maintenance of information and design model integrity 1. Single information source 2. Automated clash checking	Industry Foundation Classes (IFC) models facilitate a neutral and seamless exchange of data among various software tools and stakeholders and keep information consistency throughout the project lifecycle. An integrated cloud platform is utilized for storage of relevant information as opposed to 2D CAD drawings which maintains a single information source throughout the project life cycle.	(Lee et al, 2018) (Borrmann et al, 2018)
	Automated generation of drawings and documents	Misunderstanding and misinterpretation of design can be avoided since all teams will work on the same model. BIM automatically reciprocate any change throughout the model and reports hence maintaining the integrity of the model. BIM facilitates automated generation of drawings, therefore, reduces time, cost and waste compared to 2D CAD drawings.	(Akponeware and Adamu, 2017) (Eastman et al, 2008; Sacks et al, 2010) (Deng et al, 2020)
	Reuse of model data for predictive analyses 1. Predictive analysis of performance 2. Automated cost estimation 3. Evaluation of conformance to program/client value	By using data model, BIM software can do engineering analysis, energy analysis, automated cost estimation, automated compliance code checking, and automated clash checking.	(Eastman et al, 2009; Sacks et al, 2010)

Table 2.1 (Continued): BIM functionalities (Sacks et al, 2010).

	BIM Functionality	Descriptions	Source
Design and	Collaboration in design and construction	Collaboration happens both internally-with an organization or discipline, and externally-where people collaborate outside various disciplines during design and construction. BIM enables various disciplines to edit and view single and edited models.	(Lee et al, 2018; Oraee et al, 2017)
	1. Multiuser editing of a single discipline model		
	2. Multiuser viewing of merged or separate multidiscipline models		
	5D model-based cost estimation	BIM enabled software store information and ensure ubiquitous access to this information during the whole life cycle.	(Oskouie et al., 2012)
Preconstruction and construction		Early design coordination would improve value engineering and cost estimation by minimization of uncertainty.	(Forgues et al, 2012)
	Rapid generation of multiple design alternatives	Parametric design provides the means for rapid generation of design alternatives. This principle allows to offer multiple design options to the customer and avoid late customer-initiated changes.	(Sacks et al, 2010)
	1. Automated generation of construction tasks		
	2. Construction process simulation		
	3. 4D visualisation of construction schedules		
	Online/electronic object-based communication	Provides all stakeholder with access to relevant, up-to-date, and on time information which enhance the collaboration and consistency throughout the project life cycle.	(Oliver et al, 2020; Teicholz, 2013)
	1. Visualisations of process status		
	2. Online communication of product and process information		
	3. Computer-controlled fabrication	Allows for real-time monitor of project progress. Precise and updated information equip the stakeholders with an effective decision-making in order to meet the functional, aesthetic, and economic requirements of project stakeholders.	(Han and Golparvar-Fard, 2015; Mahdjoubi et al, 2013; Matthews et al., 2015)
	4. Integration with project partner (supply chain) databases		
	5. Provision of context for status data collection on site/off site		
	Support for augmented reality	BIM data is used to augment reality in three cases: i) Revision of prospected design in design phase, ii) Monitor of construction of phase and iii) Review of final project.	(Dunston, 2009; Meza et al. 2014)

Lean Principles	Index	Description
	A	By testing the design against performance intent and mitigate late client-involvement, automated, error-free and accurate

Lean Principles

Index

Descriptions

Source

Reduce variability

1. Get quality right the first time (reduce product variability)
2. Focus on improving upstream flow variability (reduce production variability)

A By testing the design against performance in order to meet design intent and mitigate late client-initiated changes, automated, error-free and accurate quantity take-off, removal of inconsistency among various information/representation views by introduction of single model for all reports and documents, utilisation of software (such as Solibri/Navisworks/Tekla).

B For clash identification and error free installation on site, first run studies by discrete event simulation, direct delivery of information for flow improvement, detection of flaws and incomplete design by building modelling, clash checking by integration of multiple disciplines, automated planning, up to date access to information for conflict resolution.

(Eastman et al, 2008; Khemlani 2009; Dehlin and Olofsson 2008)

Reduce cycle times

1. Reduce production cycle durations
2. Reduce inventory

C Quick performance analysis, cost estimation, client's requirements capture, parallel processing on multiple workstations, model-based coordination between disciplines, KanBIM visualisation, online visualisation and management process are used for reducing cycle times.

Lean employs single piece flow in order to reduce the cycle time due to batching.

(Sacks et al, 2009;
Eastman et al, 2008; Sacks
et al, 2010)

Reduce batch sizes

E The advantages of reduced cycle time are rapid delivery to the customer and reduction of inventory.

(Sacks et al, 2009; Sacks and Goldin, 2007; Koskela, 1992)

Table 2.2 (Continued): Lean principles (Sacks et al, 2010).

Lean Principles		Descriptions	Source
Increase flexibility	F	Use of multiskilled teams and reduction of changeover time	(Sacks et al, 2010)
1. Reduce changeover times	G	increase the flexibility in construction industry.	
2. Use multiskilled teams			
Select an appropriate production control approach	H	Unlike push system, which push the planned activities into realization, pull capture demands from customers.	(Sacks et al, 2010)
1. Use pull systems	I	Lookahead planning in last planner system a pull planning in the construction project.	
2. Level the production			
Standardise	J	Reduces both temporal and product features variability, therefore, enable continuous improvement.	(Sacks et al, 2010)
Use continuous improvement	K	Continuous improvement improves workflow by elimination of waste and defects. Continuous improvement learns from previous action and seeks for perfection.	(Sacks et al, 2010; Belhadi et al, 2020; Bicheno and Holweg, 2016; Womack et al, 1997)
Use visual management	L	Visual management supports standardisation, and connected to continuous improvement.	(Sacks et al, 2010; Alhuraish et al, 2016)
1. Visualise production methods	M	Visual management enables workers' perception of production process.	
2. Visualise production process			
Design the production system for flow and value	N	This principle emphasises that production system should be	(Sacks et al, 2010)
1. Simplify	O	designed in the way that flow and improve value for the end users.	
2. Use parallel processing	P	Approaches advised is simplification, parallel processing, and use	
3. Use only reliable technology	Q	of reliable technology.	
4. Ensure production system capability			
Ensure comprehensive requirement capture	R	Requirement capture is about value generation.	(Sacks et al, 2010)

Table 2.2 (Continued): Lean principles (Sacks et al, 2010).

Lean Principles		Descriptions	Source
Focus on concept selection	S	Generally, there is a propensity toward detailed design while lean emphasizes a set-based design and concept design.	(Parrish et al, 2007)
Ensure requirement flow down	T	Ensure that all requirements flow down to the point where the smallest parts of the product are designed and produced.	(Sacks et al, 2010)
Verify and validate	U	All value generation through designs and products should verified against specifications and validated against customer requirements.	(Stevens et al, 1998; Sacks et al, 2010)
Go and see for yourself	V	This principle emphasises to go the real place where work is performed in order to access first-hand knowledge for decision-making rather than information from others which might be biased, outdated.	(Liker, 2003)
Decide by consensus, consider all options	W	This principle underscores the importance of set-based approach for decision making which is consideration of all options that will ensure best possible solution.	(Liker, 2003)
Cultivate an extended network of partners	X	Build a long-term partnership and develop common goals with all stakeholders since a reliable supply chain requires it. Build a team who understands and follows your company's philosophy and transfers it to others.	(Sacks et al, 2010; Liker 2003)



BIM functionality	Lean principles																							
	Reduce variability		Reduce cycle times		Reduce batch sizes	Increase flexibility	Select an appropriate production control approach			Standardize	Institute continuous improvement	Use visual management		Design the production system for flow and value				Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	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 of design alternatives	2	1	22									7	7		8									
Reuse of model data for predictive analyses	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)										
	12		15	25 (29)					37						(41)				44			47		
Online/electronic object-based communication	13	2	40	25 (29)						17			40	40		40						47		49
	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		

Figure 2.1 : Interaction matrix of lean principles and BIM functionalities (Sacks et al, 2010).

2.4 A Bibliometric Analysis of BIM and Lean

Managing the information of a facility during its life cycle is becoming an arduous task due to the complex and data intensive nature of the AEC industry. The traditional exchange of information in physical blueprint on paper or narrow digital format leads to loss of consequential information during the entire building life cycle, especially, between handovers of design, construction and operation (Borrmann et al, 2018). BIM as “a modeling technology and associated set of processes to produce, communicate and analyse building models” (Sacks et al, 2018), suggests a new method for management and coordinated exchange of information among disciplines and stakeholders in order to hinder this information loss. On the other hand, the construction industry is considered as having high levels of waste (Bølviken and Koskela, 2016). A meta-analysis of construction between 1970 to 2000 by Horman and Kenley (2005) reported that almost 49.6% of construction workers spent on non-value adding activities. LC, the counterpart of lean production, aims to reduce the waste and increase the value (Gao and Low, 2014). As a new management approach, LC is a way to design production systems to minimise waste of materials, time and effort in order to generate the maximum possible amount of value (Koskela et al, 2002). Despite the benefits from their independent implementations, the synergies between BIM and LC can bolster the entire building lifecycle from design phase to handover and facility management (Dave et al, 2011) if all potentials are exploited (Sacks et al, 2010). Since the industry is pushed towards a more collaborative working environment, the acceptance of both BIM and LC, which collaboration is at their cores, should increase. Engaging these two concepts provides improved design and construction processes, and increased productivity. By aiming to understand the current status, this section focuses on illustrating a holistic synopsis of BIM and LC interaction researches through VOSviewer. The studies limited to the Scopus database and analysed from different perspectives including co-authorship, region, journal, citation and keyword co-occurrence (Eshaqzada and Ilhan Jones, 2020).

BIM and lean construction related studies were retrieved from the Scopus database, which consists of comprehensive and substantial journals. The retrieval was conducted using the following code: TITLE-ABS-KEY (“Building Information Model*” OR BIM) AND (“Lean Construction” OR LC)) AND (EXCLUDE (SUBJAREA, “BIOC”)

OR EXCLUDE (SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA, “NEUR”) OR EXCLUDE (SUBJAREA, “IMMU”) OR EXCLUDE (SUBJAREA, “PHAR”) OR EXCLUDE (SUBJAREA, “AGRI”). In order to see the interests of the research community, all types of articles including journal papers, conference papers, reviews, book chapters and short surveys were included. A total of 201 articles were examined. It covers the first quarter of 2020. Figure 2.3 illustrates the published records by year. The VOSviewer tool is employed for constructing and visualising bibliometric networks. In the VOSviewer, the “node” represents the publications, journals, researchers or keywords, and the “edge” indicates the relation and strength of the relation between two nodes. The minimum number of articles and the minimum citations of an author are set to a number that gives us graph, which is neither very congested nor very empty. For each network analysis, the total link strength indicates the total strength of the links of an item with other items. The analyses of co-authorship, country/region, published journal, co-citation and co-occurring keyword are respectively performed.

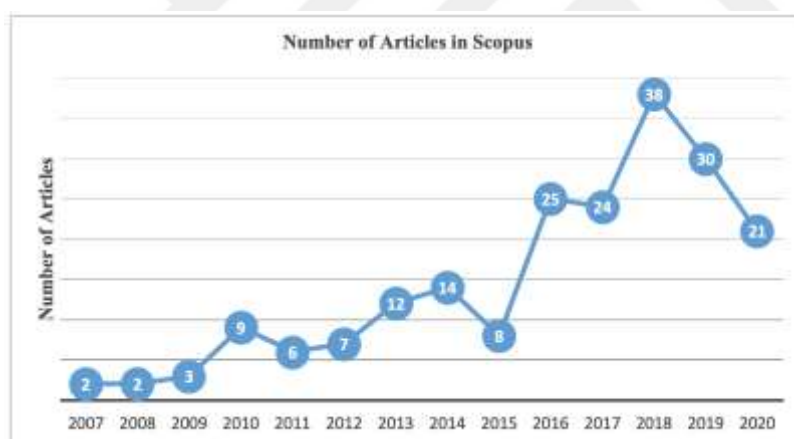


Figure 2.1 : The number of articles in Scopus between 2007–2020.

2.4.1 Co-authorship analysis

The co-authorship reveals the collaboration and cooperation among authors in BIM and LC integration. In the VOSviewer, the minimum number of articles published is determined as three and the minimum citations of an author is set at 20. 12 out of 475 authors met these criteria. After more evaluation, -some of the authors were not connected to each other- nine authors remained. Each colour represents a different cluster. The size of nodes is the number of articles published by an author. The edges show the relationships between the authors. The closer the distance, the stronger the

relationship. Having the largest node, Koskela L. has a great significance in the study of BIM and LC interactions (Figure 2.4).



Figure 2.2 : Co-authorship network.

Table 2.3 presents the details of co-authorship network. Sacks R. stands first with 621 citations, followed by Koskela L. and Dave B. with 415 and 130 citations respectively. Tezel A. is among rising academic whose publications are recent. Sacks R. has the highest average normalised citations, indicating 222% higher citations than average citations among these articles. The total link strength shows the total number of links of an author collaboration with all other authors. For example, 15 total link strength for Koskela L. indicates that Koskela L. has co-authored 15 times with others.

Table 2.3 : Details of co-authorship network.

Author	Number of Documents	Citations	Avg. Norm. Citations	Avg. Pub. Year	Total Link Strength
Koskela L.	9	415	2.27	2013	15
Dave B.	8	130	1.95	2015	12
Sacks R.	6	621	3.22	2011	2
Alarcón L.F.	5	30	0.79	2016	6
Främling K.	3	83	2.91	2015	9
Kubler S.	3	83	2.91	2015	9
Mandujano M.G.	3	26	0.95	2015	6
Mourgues C.	3	26	0.95	2015	6
Tezel A.	3	26	1.2	2018	1

2.4.2 Network of countries/regions

The minimum number of articles published and the minimum citations of an author both set at four in the VOSviewer. 16 countries/regions met the criteria but Canada and Spain were not linked to the others, so those two were excluded.

Whereas Figure 2.5 demonstrates the network of these 14 countries, Table 2.4 presents the details of country/region network. The US with 48 articles, accounting for 25.94%, has the highest performance, followed by the UK.

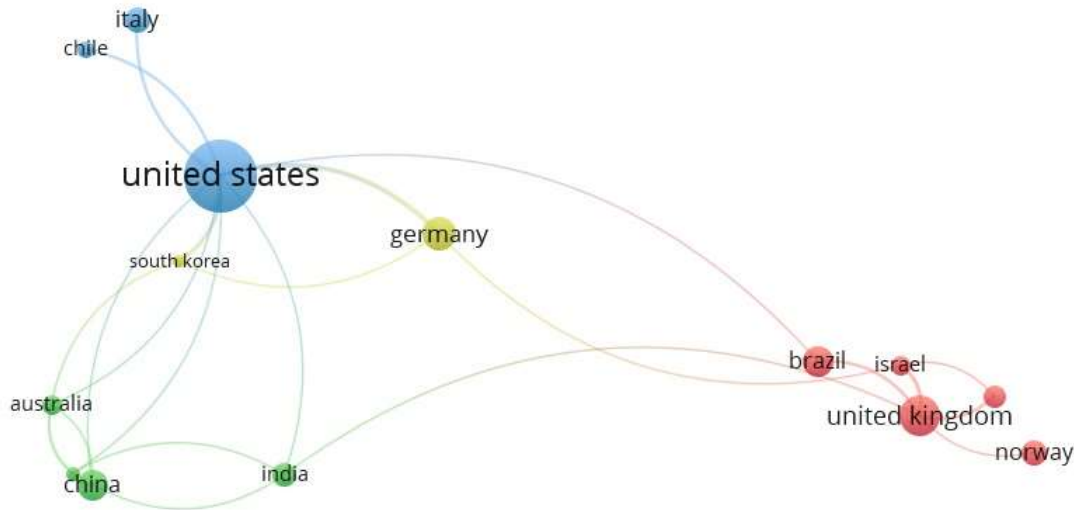


Figure 2.3 : Network of countries/regions.

Hong Kong obtained the highest value in average normalized citations, which indicates its influence in LC and BIM area. The US with greatest number of articles remains behind Israel and the UK in terms of the number of citations. For Israel, greatest number of citations can be justified as its average publication year is 2012, having an early and seminal article in this field.

Table 2.4 : Details of countries/regions network.

Country/Region	Documents	Citations	Avg. Pub. Year	Avg. Norm. Citations	Total Link Strength
United States	48	412	2015	1.2	16
United Kingdom	21	574	2016	1.54	9
Germany	16	211	2016	1.08	6
Brazil	14	74	2017	1.17	3
China	14	45	2017	0.87	6
Italy	11	46	2018	1.7	2
Norway	11	13	2018	0.64	1
India	10	40	2018	0.38	4
Finland	9	123	2016	1.52	3
Australia	8	127	2016	2.45	5
Israel	8	631	2012	2.62	5
Chile	6	36	2016	0.76	2
Hong Kong	5	88	2017	3.12	7
South Korea	4	57	2016	1.72	5

2.4.3 Network of published journals

Journals that published articles on LC and BIM synergies are shown in Figure 2.6 and Table 2.5. Minimum number of documents and the minimum number of citations were chosen as two and five respectively. Out of 31 sources, 7 met the threshold but *International Journal of Managing Projects in Business* was removed since it was not connected to others. *Automation in Construction* and *Journal of Construction Engineering and Management* are at the centre and show their significance in the BIM and LC field.

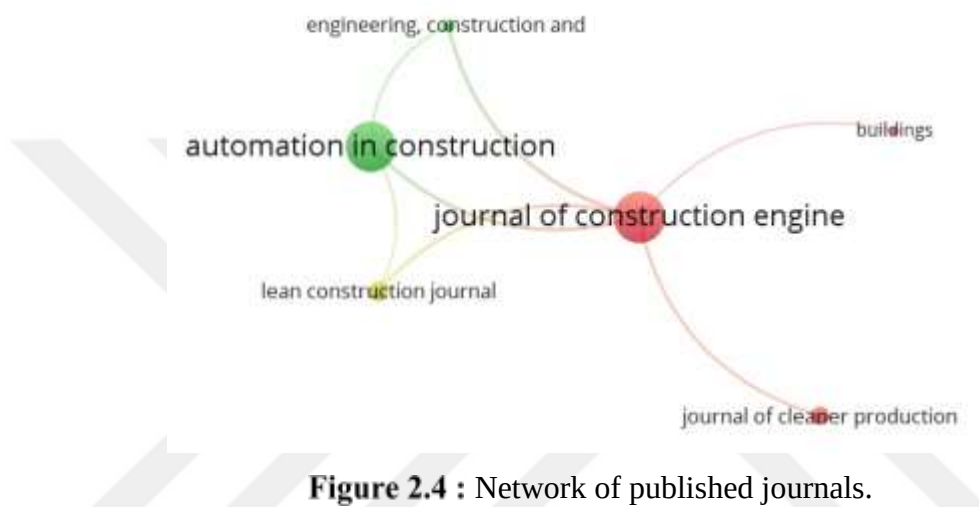


Figure 2.4 : Network of published journals.

Table 2.5 : Details of published journals.

Full Name of Journal Sources	Documents	Citations	Total Link Strength	Avg. Citations	Avg. Norm. Citations
Automation in Construction	6	385	10	64.17	1.83
Lean Construction Journal	6	58	4	9.67	0.81
Journal of Construction Engineering and Management	5	414	12	82.8	1.60
Engineering, Construction and Architectural Management	3	27	4	9	1.18
Journal of Cleaner Production	2	51	2	25.5	2.76
Buildings	2	6	2	3	0.67

Journal of Construction Engineering and Management and *Automation in Construction* have top citations while average normalized citation for *Journal of Cleaner Production* is higher with only two journal papers.

2.4.4 Network of article citations

Citation analysis in bibliometric analysis reveals the most momentous and pivotal papers in BIM and LC integration. Minimum number of 25 citations for each article were selected in VOSviewer. From 201 articles, 16 met the threshold but later narrowed down to 11 since five of them were not connected to each other. Sacks R. (2010a) and (2010b) being the most cited papers, have strong connections with others (Figure 2.7).

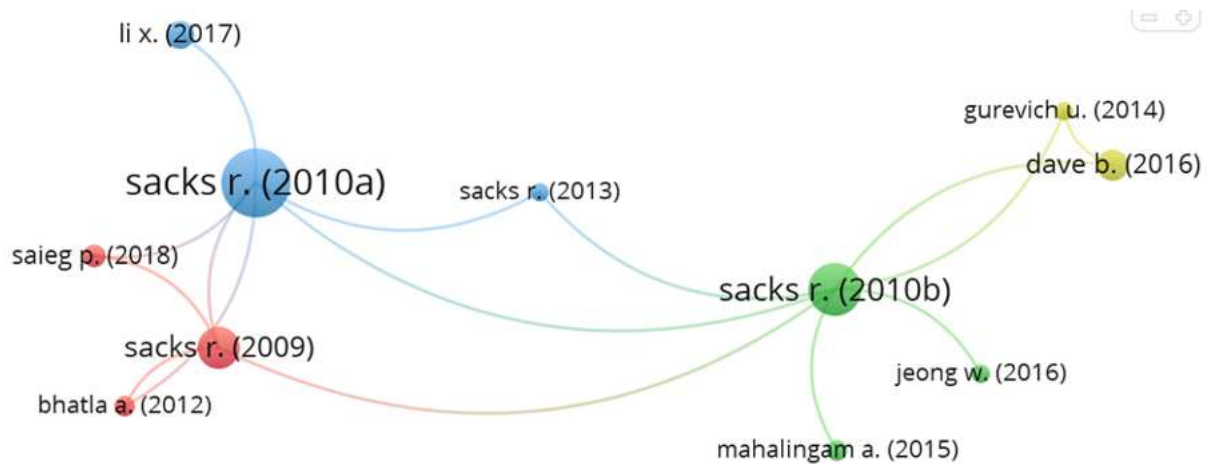


Figure 2.5 : Citation of articles.

Besides simply BIM and LC interactions, sustainability and Internet of Things (IoT) related studies are also present among the most cited articles (Table 2.6).

Table 2.6 : Details of articles citations.

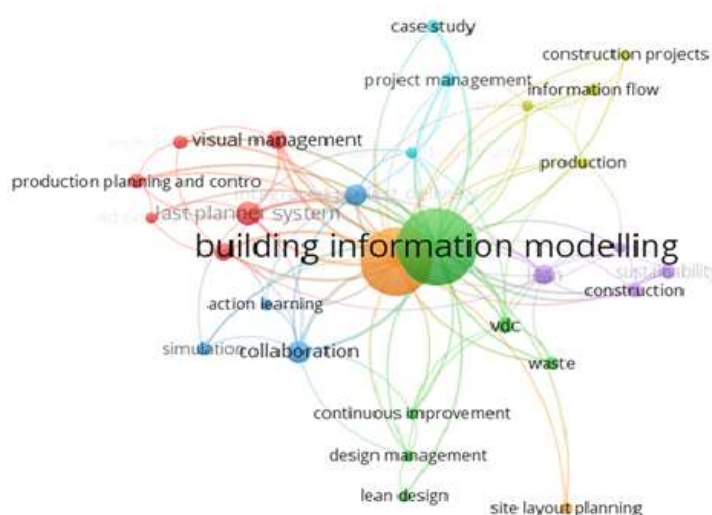
Article	Title	Citations	Norm. Citations
Sacks R. (2010a)	Interaction of lean and building information modeling in construction	262	4.35
Sacks R. (2010b)	Requirements for building information modeling based lean production management systems for construction	169	2.81
Sacks R. (2009)	Visualization of work flow to support lean construction	112	2.47
Dave B. (2016)	Opportunities for enhanced lean construction management using Internet of Things standards	66	6.81
Li X. (2017)	Mapping the knowledge domains of building information modeling (BIM): A bibliometric approach	56	7.78
Saieg P. (2018)	Interactions of building information modeling, lean and sustainability on the architectural, engineering and construction industry: A systematic review	40	11.18

Table 2.6 (Continued): Details of articles citations.

Bhatla A. (2012)	Integration framework of BIM with the last planner system TM	34	2.94
Mahalingam A. (2015)	Investigating the role of lean practices in enabling BIM adoption: Evidence from two Indian cases	32	1.6
Jeong W. (2016)	BIM-integrated construction operation simulation for Just-in-time production management	28	2.89
Sacks R. (2013)	KanBIM workflow management system: Prototype implementation and field testing	28	4.6
Gurevich U. (2014)	Examination of the effects of a KanBIM production control system on subcontractors' task selections in interior works	27	4.55

2.4.5 Network of co-occurring keywords

Keywords co-occurrence reveals the recent research trends and core of research in this area. It can help spot new BIM-LC related research topics. A standardisation approach was adopted to merge variant terms (e.g., “BIM”, “building information modeling”, “building information models” are merged into “building information modelling”). The frequency of keywords co-occurrence was set at three. 29 out of 467 keywords matched the threshold (Figure 2.8). Being BIM an LC the basis of visualisation, BIM (green) and LC (orange) are the largest nodes, 128 and 102 respectively. Other co-occurring keywords are “collaboration”, “IPD”, “last planner system”, “lean”, “visual design construction”, “augmented reality” and “waste”.

**Figure 2.6 :** Network of co-occurrence keywords.

By evaluating the research trends on BIM and LC, which are the focal points of researchers in the last two decades, this section outlines the status quo of BIM and LC

studies statistically. It highlights the influential articles, authors, journals, countries and relevant research areas about BIM and LC interactions. Beyond the overview of BIM and LC, this work also suggests new research areas such as IoT and sustainability in alignment with BIM and LC. Since BIM fulfils some LC principles greatly through the new way of producing and managing the information as well as the improvement of the workflows for many stakeholders; exploring BIM and LC studies and their possible integration with other technologies is of great importance for enhancing the design and construction processes.



3. RESEARCH METHOD

This study aims to provide a solid foundation for interaction of BIM and LC. For an effective response to the aim and objectives, a two-step method is adopted in this thesis: (1) bibliometric analysis of BIM and LC and (2) survey analysis. Figure 3.1 represents the flow and stages of the research method. Whilst the first step investigates the extant literature and find BIM functionalities and LC principles, second step conducts a survey and analyses the results through Delphi technique in order to build a consensus among respondents about BIM and LC. The study is considered to help companies and researchers internalise BIM and LC adoption.

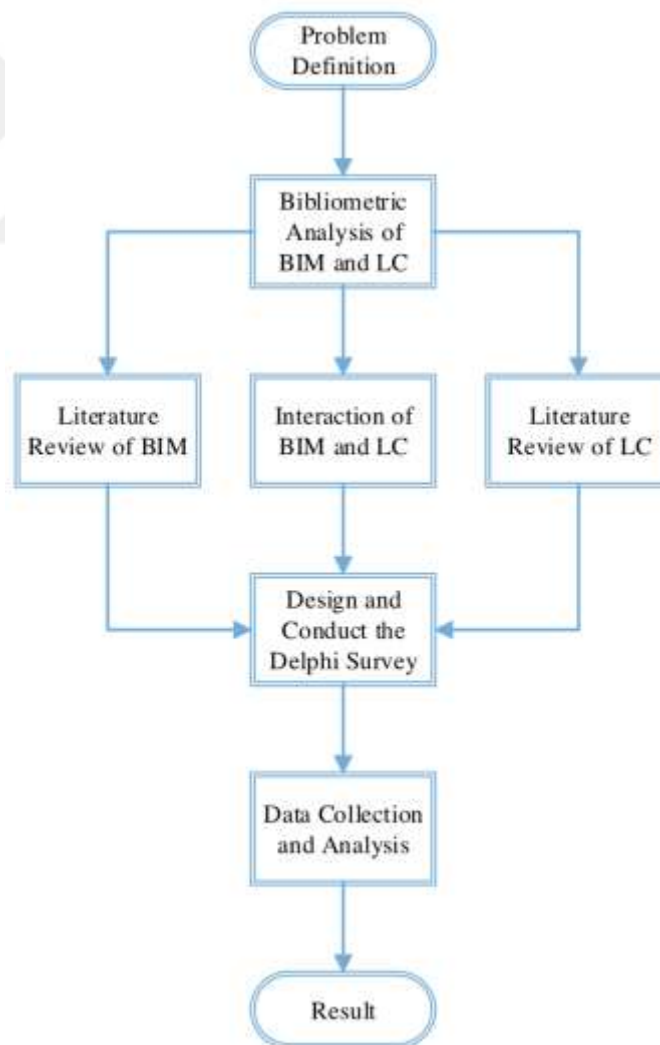


Figure 3.1 : Research method.

To carry out detailed background analysis, Scopus database were chosen for extraction of data and VOSviewer were used to conduct the analysis. The bibliometric analysis enabled us to find the influential authors, journals, and papers (please see Section 2 for further details). Then thorough literature review was conducted on BIM and LC. The literature review was conducted to find out the BIM functionalities, LC principles and finally their synergies. This literature review was useful to find a basis for future research and uncover the knowledge gap. Based on the seminal articles from preeminent journals, a literature review of BIM was conducted to ascertain the benefits of BIM to all stakeholders as well as the usage of BIM in various stages of construction. Furthermore, a literature review on LC was conducted including lean principles in construction and lean tools and techniques. Finally, the interaction matrix for BIM functionalities and LC principles was highlighted.

Following the literature review, the survey was designed by adapting the interaction matrix developed by Sacks et al. (2010). Google Forms, which is a web-based survey package, was used to gather the information from respondents due to its easiness and flexibility. The questions of the survey, including both demographic details of the respondents and the interaction matrix of BIM and LC, are given in Appendix B: Survey for BIM and LC Interaction: A Delphi Method. The survey targeted experts from industry practitioners who have experience of BIM and/or LC.

As a reliable measurement instrument, Delphi method was adopted to analyse the expert opinions for effective results.

The Delphi method is a structured method for forecasting with reliance on judgement of experts (Brown et al, 1968). Traditionally, experts have been discussing to reach a group solution to a problem but psychological factors such as persuasive personality, conformity, presence of dominant, unwillingness to change publicly expressed opinion have undermined this approach. The Delphi method is an iterative process, and elicits and distills anonymous judgements of experts without direct confrontation. Hallowell and Gambatese (2010) defined the Delphi survey technique as a “systematic and interactive research technique to obtain the judgment of a group of experts on a specific topic”. The Delphi method was invented by Helmer Dalkey of RAND Corporation in 1950s to construct consensus forecasts from group of experts for specific military problems.

Helmer and Rescher (1959) emphasize that Delphi method negates the misleading persuasion, bandwagon effect and resistance for abandoning the publicly expressed opinion. The Delphi method can also be used both as a decision-aiding and estimation tool (Rowe and Wright, 1999) and when there is an incomplete knowledge about a problem (Adler and Ziglio, 1996). Usually, a 2-3 round of Delphi survey is sufficient to achieve a consensus among experts (Giel and Issa, 2016).

A two-round Delphi survey was carried out for this study and after the analysis of second round, it was ensured that a consensus is reached. After the panel of experts (a total of 25) was selected, they were given the surveys. The main criteria for selecting the participants were their knowledge in BIM and LC. A total of 13 experts responded the survey. In the first round, they were asked to indicate and identify the interaction of BIM and LC. In the second round, the experts were given the feedback on the result from Round 1 and asked to change or sustain wherever they think it fits. Moreover, the anonymity of the experts was maintained. Based on their judgments, the results were analysed. Figure 3.2 displays the Delphi survey processes.

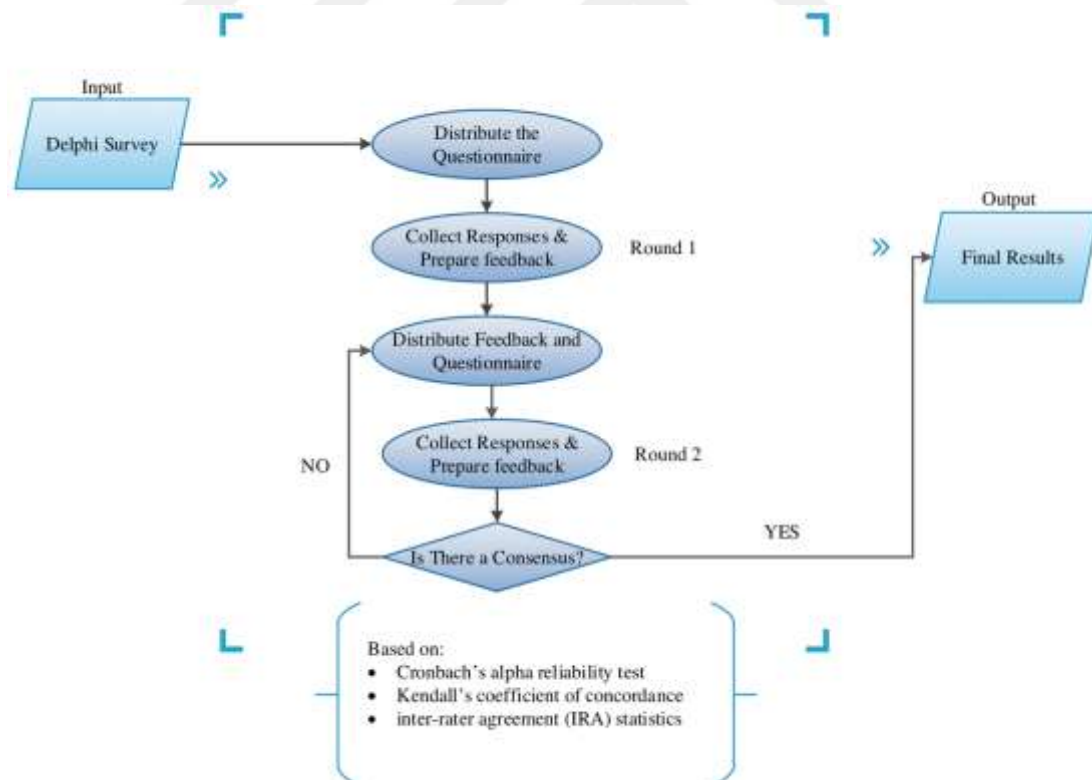


Figure 3.2 : Delphi survey stages.



4. DATA ANALYSIS AND FINDINGS

In order to analyse the responses from the panel of experts, descriptive statistical tools were used. These tools include Cronbach's alpha reliability test, Kendall's coefficient of concordance and inter-rater agreement (IRA) statistics. The findings of the study are presented in three parts. The first part provides the general information of the participants, while the second and third parts present the results for the rounds of the Delphi survey.

4.1 Expert Panels' Demographics

13 experts participated in a two-round Delphi survey. 46.2% percent of the panels are architects whereas, 46.2% percent and 7.7% percent had studied civil engineering and electrical engineering respectively. All except one of the panellists are using either BIM or adopt lean approach in their companies. 23.07% percent of the experts are BIM manager, 38.46% percent are BIM modeller and 38.46% percent are BIM coordinator. 7.7% percent has 11-15 years of experience, 3.8% percent has 6-10 years of experience, 46.2% percent has 2-5 years of experience, and 15.4% percent has less than 2 years of experience. Table 4.1 demonstrates the profile of the panellists.

Table 4.1 : Demographic of the respondents.

Expert ID	Education Level	Field of Study	Position	Experience (Years)	BIM user
E1	BSc	Civil Engineering	Coordinator	Less than 2 years	No
E2	PhD	Architecture	Modeller	2-5 years	Yes
E3	MSc	Architecture	Modeller	6-10 years	Yes
E4	BSc	Civil Engineering	Coordinator	2-5 years	Yes
E5	PhD	Electrical Engineering	Modeller	6-10 years	Yes
E6	MSc	Architecture	Manager	11-15 years	Yes
E7	MSc	Civil Engineering	Coordinator	2-5 years	Yes

Table 4.1 (Continued): Demographic of the respondents.

Expert ID	Education Level	Field Of Study	Position	Experience (Years)	BIM user
E8	BSc	Architecture	Modeller	2-5 years	Yes
E9	MSc	Civil Engineering	Modeller	2-5 years	Yes
E10	MSc	Civil Engineering	Manager	6-10 years	Yes
E11	BSc	Architecture	Coordinator	2-5 years	Yes
E12	MSc	Architecture	Coordinator	6-10 years	Yes
E13	BSc	Civil Engineering	Manager	Less than 2 years	Yes

4.2 BIM and Lean Interaction – Round 1

In the first round, experts' opinions were asked to identify and state the interactions between BIM functionalities and lean principles. The experts were asked to indicate which BIM functionality supports which lean principle from the matrix. The results, then, were analysed by identifying that what percentage of the experts have voted for each interaction. Figure 4.1 shows the results of Round 1, including BIM functionalities in the columns and lean principles tabulated in the rows. In this round, among all the highest frequencies belong to A1, K2, D2, B2, B5, and P6, [i.e., Visualisation of form and reduce variability, Rapid generation of multiple design alternatives and Focus on concept selection, Rapid generation of multiple design alternatives and Increase flexibility, Rapid generation of multiple design alternatives and Reduce cycle times, Automated generation of drawings and documents and Reduce cycle times, Collaboration in design and construction and Cultivate an extended network of partners]. The respondents have chosen the interactions between them. The interactions with higher frequencies are highlighted with blue. After this analysis, the results were sent back to the participants to adjust if they do not agree with the other panellists' responses or maintain their original opinions.

BIM Functionality		Lean Principles															
		Reduce variability	Reduce cycle times	Reduce batch sizes	Increase flexibility	Select an appropriate production control approach	Standardize	Institute continuous improvement	Use visual management	Design the production system for flow and value	Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	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
Visualization of form	1	76.92%	23.07%	30.77%	38.46%	30.77%	23.07%	46.00%	76.92%	30.77%	30.77%	53.85%	15.38%	38.46%	38.46%	30.77%	30.77%
Rapid generation of multiple design alternatives	2	53.84%	76.92%	30.77%	76.92%	23.07%	30.77%	53.85%	38.46%	38.46%	38.46%	76.92%	46.15%	30.77%	23.07%	61.54%	15.38%
Reuse of model data for predictive analyses	3	38.46%	53.84%	38.46%	23.07%	23.07%	46.15%	30.77%	15.38%	53.85%	38.46%	38.46%	53.85%	46.15%	30.77%	46.15%	30.77%
Maintenance of information and design model integrity	4	61.53%	61.54%	30.77%	30.77%	69.23%	61.54%	61.54%	38.46%	53.85%	46.15%	23.07%	30.77%	61.54%	30.77%	38.46%	23.07%
Automated generation of drawings and documents	5	46.15%	76.92%	53.85%	38.46%	38.46%	61.54%	30.77%	30.77%	53.85%	30.77%	30.77%	38.46%	23.07%	23.07%	38.46%	15.38%
Collaboration in design and construction	6	46.15%	53.85%	30.77%	30.77%	46.15%	15.38%	53.85%	46.15%	38.46%	38.46%	30.77%	30.77%	53.85%	53.85%	61.55%	76.92%
Evaluation of construction plan alternatives	7	30.76%	30.77%	30.77%	30.77%	38.46%	23.07%	53.85%	30.77%	38.46%	23.07%	30.77%	30.77%	38.46%	38.46%	30.77%	38.46%
Online/electronic object-based communication	8	30.76%	61.54%	46.15%	38.46%	23.07%	53.85%	38.46%	30.77%	38.46%	30.77%	23.07%	30.77%	38.46%	38.46%	38.46%	61.54%

Figure 4.1 : Results of round 1 – Delphi method: Interaction of BIM and LC principles.

4.3 BIM and Lean Interaction – Round 2

In the second round of the Delphi survey, differently from the first round, some statistical analyses were carried out in order to validate the responses. For this reason, the IBM®SPSS® Statistics (“SPSS”) Version 26 was used to examine the data. First, the Cronbach’s alpha (α) test is employed to test the internal consistency in which whether the questionnaire measures the right constructs or not. The alpha value ranges from 0 to 1, and Nunnally (1978) suggests a minimum of Cronbach’s α value of 0.7 is acceptable. The Cronbach’s α value for our survey is 0.753. The following formula is used for the calculation of Cronbach’s alpha:

$$\alpha = \frac{n}{n-1} \left(1 - \frac{\sum_{i=1}^n \sigma_i^2}{\sigma_X^2} \right) \quad (4.1)$$

where n is the number of variables, σ_i^2 is the score variations on each variable and σ_X^2 is the total variance of the overall score.

Moreover, a Shapiro-Wilk test is applied to test for normality if the dataset is normally distributed or not. The 128 interactions have a significance level of ($P < 0.05$), which demonstrates a non-normally distributed dataset, thus a non-parametric statistical approach is used. In order to rank the interactions, mean scores or μ is used as the main criteria and if two interactions had the same mean score, then the smaller standard deviation (SD or σ) is ranked first. Moreover, if they had both equal mean and SD, then variance (σ^2) was also employed. If all three parameters are equal, then they are in the same level. Mean scores, standard deviation, and variance values of the second round for the eight BIM functionalities and sixteen lean principles are indicated in Figure 4.2 and Table 4.2. Mean scores for the interactions of eight BIM functionalities and sixteen lean principles identified in the second round of the Delphi survey ranges from [$\mu = 4.85$, $\sigma = 0.376$ and $\sigma^2 = 0.141$] for “A1: Visualisation of form and Reduce variability” to [$\mu = 1.08$, $\sigma = 0.277$ and $\sigma^2 = 0.077$] for “B7: Rapid generation and Evaluation of construction plan alternatives and Reduce cycle times”. Zahoor et al. (2017) adopted a scale interval for understanding the importance of a factor for five-point Likert scale as follows: ($\mu > 4.51$) “extremely important”, ($3.51 < \mu < 4.5$) “very important”, ($2.51 > \mu > 3.5$) “important”, ($1.51 > \mu > 2.5$) “some-what important” and ($\mu < 1.5$) “not important”.

BIM Functionality		Lean Principles															
		Reduce variability	Reduce cycle times	Reduce batch sizes	Increase flexibility	Select an appropriate production control approach	Standardize	Institute continuous improvement	Use visual management	Design the production system for flow and value	Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	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
Visualization of form	1	4.85	2.31	2.23	2.46	2.23	2.31	2.38	4.69	4.54	4.38	2.38	3.92	4.23	4.62	4.31	2.54
Rapid generation of multiple design alternatives	2	4.38	4.69	2.92	4.54	2.15	2.23	3.00	4.46	4.46	2.54	2.92	2.62	2.08	1.54	2.92	2.15
Reuse of model data for predictive analyses	3	4.23	4.85	4.54	4.54	2.69	2.46	2.31	1.46	4.62	4.31	4.31	4.00	4.23	1.77	2.38	2.46
Maintenance of information and design model integrity	4	4.31	4.62	2.38	2.46	2.08	2.08	2.62	2.38	2.69	2.62	1.69	4.62	4.54	2.46	2.92	1.69
Automated generation of drawings and documents	5	4.54	4.69	4.62	2.92	2.31	2.92	2.62	2.54	4.23	3.08	1.85	2.92	2.08	2.46	2.23	1.92
Collaboration in design and construction	6	4.54	4.77	3.31	4.08	4.31	1.23	2.23	3.00	4.08	4.46	2.92	4.31	4.77	2.92	4.54	4.54
Rapid generation and Evaluation of construction plan alternatives	7	4.62	1.08	2.33	4.00	4.54	4.54	4.54	4.54	1.31	1.38	2.85	2.77	4.15	3.15	4.08	2.85
Online/electronic object-based communication	8	4.38	4.77	4.31	4.69	2.46	4.08	4.38	2.08	1.23	1.62	2.69	2.46	4.23	4.23	2.77	4.62

(Green) “extremely important”, (Blue) “very important”, (Yellow) “important”, (Grey) “some-what important” and (red) “not important”.

Figure 4.2 : Results of round 2 – Delphi method: Interaction of BIM and LC principles (mean).

Table 4.2 : Results of round 2 – Delphi method: Interaction of BIM and LC principles (Standard deviation).

BIM Functionality		Lean Principles															
		Reduce variability	Reduce cycle times	Reduce batch sizes	Increase flexibility	Select an appropriate production control approach	Standardize	Institute continuous improvement	Use visual management	Design the production system for flow and value	Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	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
Visualization of form	1	0.376	0.630	0.599	0.519	0.439	0.630	0.506	0.480	0.519	0.506	0.506	1.188	0.439	0.506	0.480	0.519
Rapid generation of multiple design alternatives	2	0.506	0.480	0.277	0.519	0.376	0.439	0.000	0.519	0.519	0.519	0.277	0.506	0.277	0.660	0.277	0.689
Reuse of model data for predictive analyses	3	0.439	0.376	0.519	0.519	0.630	0.519	0.630	0.519	0.506	0.480	0.480	0.913	0.439	0.599	0.506	0.519
Maintenance of information and design model integrity	4	0.480	0.506	0.506	0.519	0.277	0.277	0.506	0.650	0.630	0.506	0.630	0.506	0.519	0.519	0.277	0.630
Automated generation of drawings and documents	5	0.519	0.480	0.506	0.494	0.480	0.277	0.506	0.519	0.439	0.641	0.801	0.494	0.277	0.519	0.439	1.038
Collaboration in design and construction	6	0.519	0.439	0.630	0.641	0.480	0.439	0.439	0.000	0.641	0.519	0.277	0.480	0.439	0.277	0.519	0.519
Rapid generation and Evaluation of construction plan alternatives	7	0.506	0.277	0.492	0.707	0.519	0.519	0.519	0.519	0.855	0.650	0.376	0.439	0.555	0.376	0.494	0.689
Online/electronic object-based communication	8	0.506	0.439	0.480	0.480	0.519	0.277	0.506	0.954	0.599	0.870	0.480	0.519	0.439	0.439	0.439	0.506

	Legend																	
		Shared interactions					New interactions					Literature interactions						
Stage	BIM Functionality		Lean Principles															
			Reduce variability	Reduce cycle times	Reduce batch sizes	Increase flexibility	Select an appropriate production control approach	Standardize	Institute continuous improvement	Use visual management	Design the production system for flow and value	Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	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
Design	Visualization of form	1	+							+	+	+		+	+	+	+	
	Rapid generation of multiple design alternatives	2	+	+		+				+	+							
	Reuse of model data for predictive analyses	3	+	+	+	+				-	+	+	+	+	+			
	Maintenance of information and design model integrity	4	+	+										+	+			
	Automated generation of drawings and documents	5	+	+	+							+						
Design and fabrication detailing	Collaboration in design and construction	6	+	+		+	+	-			+	+		+	+		+	+
Preconstruction and construction	Rapid generation and evaluation of construction plan alternatives	7	+	-		+	+	+	+	+	-	-			+	+	+	
	Online/electronic object-based communication	8	+	+	+	+	+	+	+	+	-			+	+	+	+	+

Figure 4.3 : Superimposition of literature and newly suggested interactions.

Figure 4.3 demonstrates the superimposition of interactions found in the literature and new suggested interaction by the respondents. The mixed colour shows the shared interactions while the blue colour signifies the interaction specific to the literature and orange colour shows newly suggested interactions by participants in this study. The (+) sign indicates the positive interaction while (-) sign shows the negative interaction.

Moreover, the results of the second round of Delphi survey indicate that all participants have changed the ranking compared to the first round. In the first round, for instance, the top ten interactions with high frequency were A1, B2, D2, K2, B5, P6, E4, A4, B4, and B8, while in the second round; A1, B3, B8, M6, B6, H1, B2, B5, D8, and B4 are the interactions with high frequency. On the other hand, the five interactions with less frequency are L1, P2, P5, H3, K4, J7, F1, N2, E2, and E3 for the first-round while in the second round, the interactions with less mean score are B7, F6, I8, I7, J7, H3, N2, J8, P4, and K4. These results show that some participants have changed and adjusted their decision in the second round of the Delphi survey.

“Kendall’s” coefficient of concordance (W) non-parametric test was applied using IBM® SPSS® Statistics to assess the level of consensus among the expert’s panel. It measures the agreement among a particular group based on the mean value (Hollander et al., 2013). The range of the value of Kendall’s coefficient of concordance (W) is from 0 to 1. Kendall’s W ranges between zero (0) and one (1), where (0) reflects a perfect disagreement among the panellists and (1) indicates a perfect agreement. The value of W is as follows:

$$W = \frac{\sum_{i=1}^n (\bar{R}_i - \bar{R})^2}{n(n^2 - 1)/12} \quad (4.2)$$

where n is the number of items ranked; $\bar{R}_i$ is the average of the ranks assigned to the item; and $\bar{R}$ is the average of the ranks assigned to all items.

The W value is 0.842 and it shows a reasonable agreement among the expert panels.

The inter-rater agreement statistics (IRA) was utilised for validation and analysis of the expert agreements. The IRA evaluates the strength of consensus among the experts. It is a significant measurement since it is independent of sample size. However, the IRA formula cannot quantify at the extreme point (i.e., 1 and 5 for a 5-point Likert

scale). Therefore, equation 4.4 and equation 4.5 are used to define the maximum and minimum limits of the mean scores for the IRA statistics. Brown and Hauenstein (2005) interpretation used for IRA analysis since it is more recent and give accurate results. Brown and Hauenstein (2005) suggested the following interpretation of the IRA evaluations.

(0.91–1.00) “very strong agreement,” (0.71–0.90) “strong agreement” (0.51–0.70) “moderate agreement,” (0.31–0.50) “weak agreement” and (0.00–0.30) “lack of agreement.”

$$a_{wg(1)} = 1 - \frac{(2 * SD^2)}{\{(A + B)M - (M^2) - (A * B)\} * \frac{n}{n-1}} \quad (4.3)$$

$$M_{min} = \frac{B(n-1) + A}{n} \quad (4.4)$$

$$M_{max} = \frac{A(n-1) + B}{n} \quad (4.5)$$

where SD= standard deviation, A= maximum scale value (i.e., 5), B= minimum scale value (i.e., 1), M= mean value of that factor, n= sample size of respondents (i.e., 13 in this study).

Table 4.3 presents the results of the IRA analysis for the interaction of BIM and LC. For example, the interaction “A1” with $a_{(wg)} = 0.984$ demonstrates a “very strong” level of agreement among the participants while “I2” with $a_{(wg)} = 0.029$ shows “lack of agreement” of participants on this interaction.

Table 4.3: IRA analysis of BIM and LC interaction.

Code	2nd round IRA $a_{(wg)}$	Agreement Level	Code	2nd round IRA $a_{(wg)}$	Agreement Level
A1	0.984	Very Strong	O2	0.983	Very Strong
B3	0.984	Very Strong	O4	0.983	Very Strong
B8	0.978	Very Strong	D5	0.945	Very Strong
M6	0.978	Very Strong	F5	0.983	Very Strong
B6	0.978	Very Strong	L5	0.945	Very Strong
H1	0.973	Very Strong	K6	0.983	Very Strong
B2	0.973	Very Strong	N6	0.983	Very Strong
B5	0.973	Very Strong	K7	0.967	Very Strong

Table 4.3 (Continued): IRA analysis of BIM and LC interaction.

Code	2nd round IRA a(wg)	Agreement Level	Code	2nd round IRA a(wg)	Agreement Level
D8	0.973	Very Strong	P7	0.889	Strong
B4	0.969	Very Strong	L7	0.953	Very Strong
L4	0.969	Very Strong	O8	0.953	Very Strong
P8	0.969	Very Strong	E3	0.898	Strong
N1	0.969	Very Strong	I4	0.898	Strong
I3	0.969	Very Strong	K8	0.941	Very Strong
C5	0.969	Very Strong	L2	0.931	Very Strong
A7	0.969	Very Strong	J4	0.931	Very Strong
D2	0.967	Very Strong	G4	0.931	Very Strong
C3	0.967	Very Strong	G5	0.931	Very Strong
P6	0.967	Very Strong	P1	0.924	Very Strong
G7	0.967	Very Strong	J2	0.924	Very Strong
I1	0.967	Very Strong	H5	0.924	Very Strong
D3	0.967	Very Strong	D1	0.920	Very Strong
M4	0.967	Very Strong	P3	0.920	Very Strong
A5	0.967	Very Strong	D4	0.920	Very Strong
A6	0.967	Very Strong	N4	0.920	Very Strong
O6	0.967	Very Strong	N5	0.920	Very Strong
E7	0.967	Very Strong	E8	0.920	Very Strong
F7	0.967	Very Strong	L8	0.920	Very Strong
H7	0.967	Very Strong	F3	0.920	Very Strong
I2	0.966	Very Strong	K1	0.920	Very Strong
J6	0.966	Very Strong	O3	0.920	Very Strong
H2	0.966	Very Strong	C4	0.920	Very Strong
J1	0.967	Very Strong	H4	0.868	Strong
A2	0.967	Very Strong	G1	0.920	Very Strong
A8	0.967	Very Strong	C7	0.921	Very Strong
G8	0.967	Very Strong	B1	0.868	Strong
O1	0.970	Very Strong	F1	0.868	Strong
J3	0.970	Very Strong	G3	0.868	Strong
K3	0.970	Very Strong	E5	0.924	Very Strong
E6	0.970	Very Strong	F2	0.932	Very Strong
L6	0.970	Very Strong	C1	0.874	Strong
C8	0.970	Very Strong	E1	0.932	Very Strong
A4	0.970	Very Strong	O5	0.932	Very Strong
M1	0.974	Very Strong	G6	0.932	Very Strong
I5	0.974	Very Strong	E2	0.947	Very Strong
M8	0.974	Very Strong	P2	0.822	Strong
A3	0.974	Very Strong	H8	0.634	Moderate
M3	0.974	Very Strong	M2	0.969	Very Strong
N8	0.974	Very Strong	E4	0.969	Very Strong
M7	0.958	Very Strong	F4	0.969	Very Strong
D6	0.942	Very Strong	M5	0.969	Very Strong

Table 4.3 (Continued): IRA analysis of BIM and LC interaction.

Code	2nd round IRA a(wg)	Agreement Level	Code	2nd round IRA a(wg)	Agreement Level
I6	0.942	Very Strong	P5	0.494	Weak
O7	0.966	Very Strong	K5	0.672	Moderate
F8	0.989	Very Strong	N3	0.798	Strong
D7	0.928	Very Strong	K4	0.751	Strong
L3	0.880	Strong	P4	0.751	Strong
L1	0.791	Strong	J8	0.467	Strong
C6	0.925	Very Strong	N2	0.649	Strong
N7	0.972	Very Strong	H3	0.747	Strong
J5	0.914	Very Strong	J7	0.523	Strong
G2	1.000	Very Strong	I7	-0.029	Lack of Agreement
H6	1.000	Very Strong	I8	0.326	Weak
C2	0.983	Very Strong	F6	0.639	Moderate
K2	0.983	Very Strong	B7	0.567	Moderate

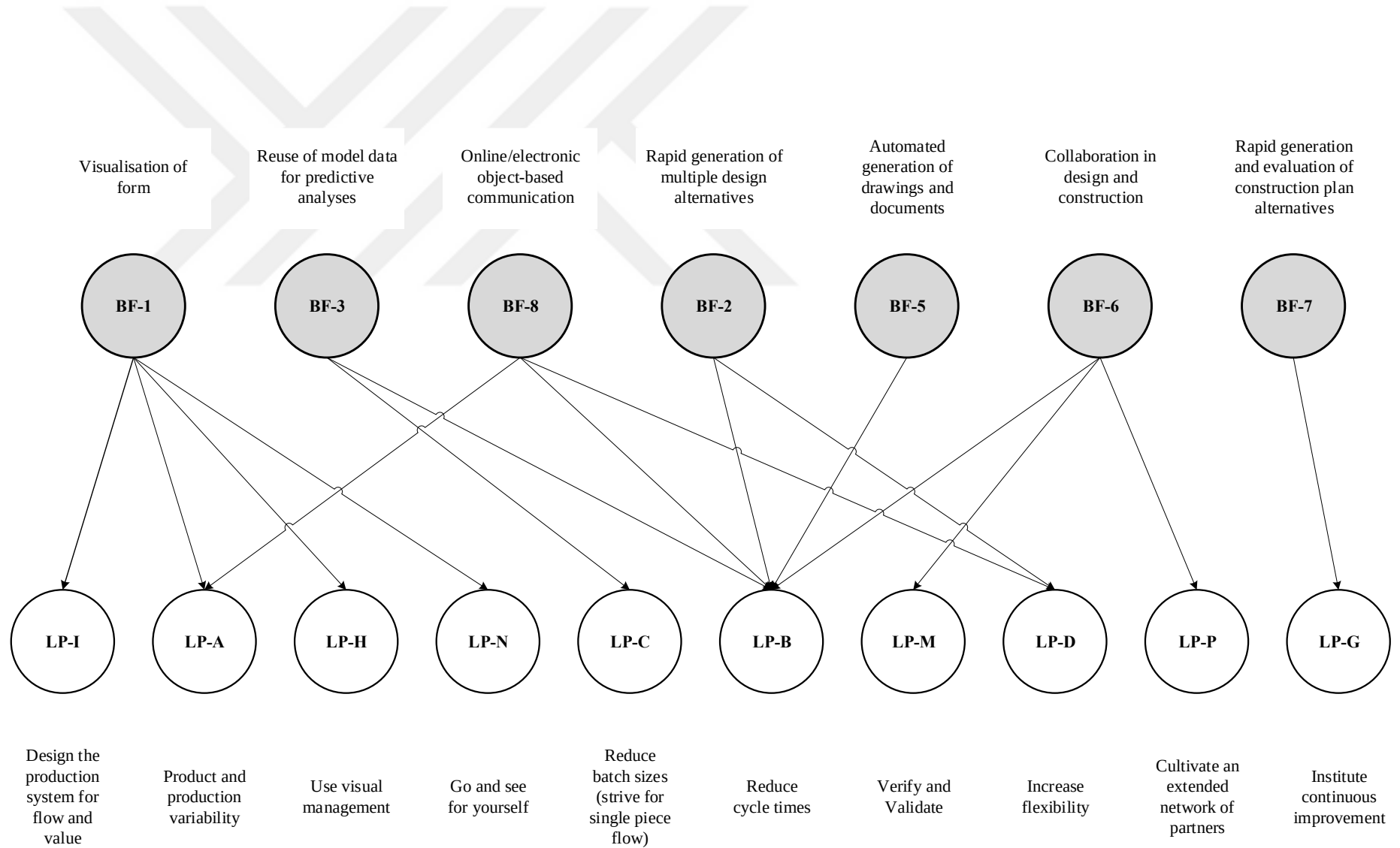


Figure 4.4 : Final positive interactions with high mean score.

Figure 4.4 shows the positive interactions between BIM functionalities and LC principles which have got the highest mean scores. On the other hand, Figure 4.5 demonstrates the negative interactions with lowest mean scores.

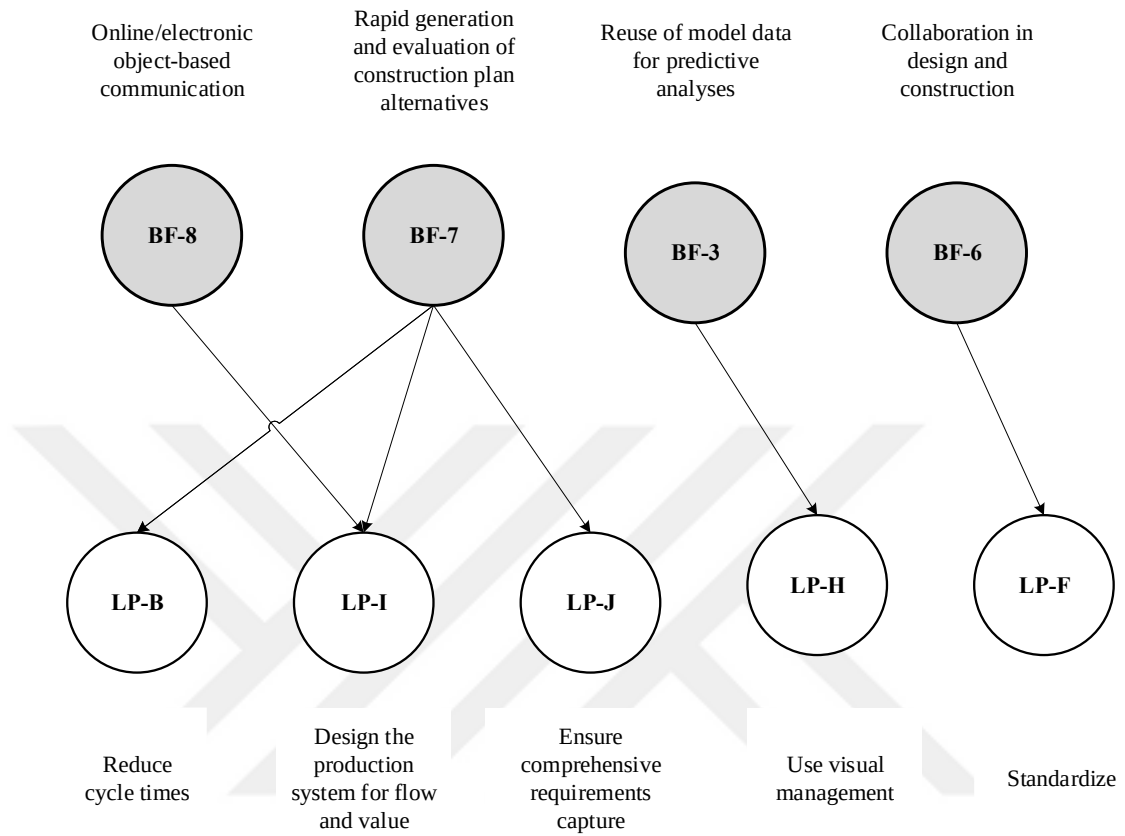


Figure 4.5 : Final negative interactions.



5. DISCUSSIONS AND CONCLUSION

This research aims to find synergies between BIM and LC. The study employed the framework suggested by Sacks et al. (2010). A total of 13 experts (6 architects, 6 civil engineers and 1 electrical engineer) participated in the survey. 3 of the panellists are BIM managers, while the number of BIM modellers and BIM coordinators is 5. By utilising this framework, a two-round Delphi survey was conducted to elicit the experts' opinions on the BIM and lean construction interaction. In the first round, the participants were asked to spot the interactions between BIM functionalities and lean principles, however, in the second round, the experts rated the interaction on a 5-point Likert scale. Some statistical tools such as Cronbach's alpha reliability test, mean score, Kendall's coefficient of concordance, and inter-rater agreement (IRA) statistics were exploited to validate the survey's results.

The results of the study suggest that there are strong synergies between BIM and LC. The findings are consistent with the body of the literature and there is a strong agreement among the expert of panels. The findings indicate both positive and negative interactions. The descriptive statistical approaches have been utilised to validate the level of agreement among the participants.

The Cronbach's alpha (α) which is 0.703, indicates that there is acceptable internal consistency for each participant. The Shapiro-Wilk test with significance level of ($P < 0.05$) showed that the dataset is non-normal distribution, therefore, non-parametric statistical approach is utilised. Mean score and standard deviation are used to ranked the interaction on the basis of 5-point Likert scale. The higher mean score indicates positive interaction while lower mean score shows negative interaction. Kendall's coefficient with W value of 0.842 demonstrates a good level of agreement among the panel of experts on the both positive, negative and neutral interactions. Finally, inter-rater agreement (IRA) is used to show the level of consensus among the participants. Consensus ranges from "very strong agreement" to "week agreement".

“Reduce product and production variability (get quality right the first time, focus on improving upstream flow variability)” (A), “reduce cycle time (reduce production cycle durations and Reduce inventory)” (B), and “increase flexibility (reduce changeover times and use multiskilled teams)” (D) have got the highest interactions. These interactions do not restrict to design phase of the project rather extend throughout the design and construction phase. The three above mentioned principles have interactions with myriad of BIM functionalities. These interactions are in aligned with that of literature but add “increase flexibility” among top lean principles that has interaction with various BIM functionalities.

BIM functionalities that received high mean score that have numerous interactions with lean principles are “collaboration in design and construction” (6), “reuse of model data for predictive analyses” (3), “online/electronic object-based communication” (8), “visualisation of form” (1), “rapid generation and evaluation of construction plan alternatives” (7). Although BIM is perceived as design tool but three out of five functionalities deal with fabrication and construction. All suggested interactions that have got high attention support the literature but highlight the “reuse of model data for predictive analyses” functionalities which have high interaction with lean principles.

On the other hand, there are lean principles that demonstrate least interactions with BIM functionalities. These principles are “design the production system for flow and value” (I), “focus on concept selection” (K), and “go and see for yourself” (N). “Design the production system for flow and value” does not support BIM since it is about simplifying the production system while generation of detailed and various construction plans complicate the production system. Literature review also indicates that principle (I) does not support BIM functionalities.

BIM functionalities that offer least interaction are “maintenance of information and design model integrity” (4), and “automated generation of drawings and documents” (5). According to this study, these BIM functionalities have good interaction with limited number of lean principles.

The study proposes multitude of interactions between BIM functionalities and lean principles besides negative interactions. Mainly, BIM is considered as a design tool while the study shows numerous interactions during construction phase of a project. For example, BIM-enabled quantity take-off reduces cycle time chiefly and

visualisation of form improve the customer's satisfaction, thus reducing the product variability.

The predominant problems with lean might be the inadequacy of conceptual understanding of lean principles. Another problem is that a lean principle may not support some BIM functionalities while support others which makes it hard for expert to spot the interaction. This can be achieved through the adoption of both BIM and LC, and continuous quest for achieving the full objectives.

The positive interactions can also be interpreted as follows:

“Visualisation of form” reduces both “product and production variability” since both physical and functional design requirements are grasped well in the early stage of design thus hinders the owner's late variation order. Moreover, automated clash checking reduces the design flaws, therefore, wastes such as “making-do” and rework are blocked.

“Reuse of model data for predictive analyses” enables performance analysis, cost estimation. This performance analyses such as structural, thermal, and acoustic; and cost estimation “reduce cycle times”.

“Online/electronic object-based communication” reduces variability because up-to-date availability of information impedes conflict and error and improve collaboration among the stakeholders. Distribution of models among the participants during the design phase ensure that all requirements are understood and agreed on. Collaboration in the early stage of the design among various disciplines such as clash checking helps detection of flaws in the early stage, therefore, reduces variability.

Visualisation of form helps the numerous disciplines to coordinate the designs with non-technical stakeholders which support the design management. Manipulation of parametric design for design alternatives and automated generation of drawings and documents reduce cycle times.

Maintenance of information and design model integrity enabled by BIM, keeps consistency of the information and reciprocate any change to all aspects of the model. Integrating all involving companies' information prop up an extended network of partnership. BIM can support the virtual visit of the worksite, therefore, “visualisation of form” enables “go and see for yourself”. Any design change of the model, will automatically be reciprocated to relevant part such as cost estimation, planning, and

production drawings. Moreover, automated generation of drawings, especially drawings of prefabrication, the production will be done in smaller batches since information is online available and accessible. BIM with the visualisation it provides, such as construction process simulation, 4D visualisation of schedules, will reduce variability by spotting conflicts and constraints before construction.

Furthermore, “rapid generation of multiple design alternatives” improves flexibility by numerous design alternatives. “Reuse of model data for predictive analyses” and “reduce batch sizes (strive for single piece flow)”, “collaboration in design and construction” and “cultivate an extended network of partners”, “rapid generation and evaluation of construction plan alternatives” and “institute continuous improvement”, “visualization of form” and “design the production system for flow and value”. Collaboration among teams will help the company to build an extended network of partners. Automated generation of construction tasks, construction process simulation, 4D visualization of construction schedules allows continuous improvement by detecting the constraints and variations. In addition, visualisation of form simplifies the design and construction processes.

“Reuse of model data for predictive analyses” allows performance analysis such as energy, acoustics, wind, and thermal which increase flexibility by detailed analyses. Furthermore, “Maintenance of information and design model integrity” by application of software such as Solibri, Navisworks, and Tekla detect clashes which validate an error-free onsite installation. “Automated generation of drawings and documents” reduce variability by maintaining a single source of information from all reports are drawn. “Collaboration in design and construction” also reduce variability by integrating all disciplines and automated clash checking as well as enables teams to share the workload and consider all options.

“Rapid generation and evaluation of construction plan alternatives” allocate the work evenly so support the pull planning and production levelling. Moreover, this functionality supports standardization by animation of installation arrangements and simulate the construction process for workers. Visualisation provided by BIM throughout the project lifecycle such as simulation of production methods, and animation of construction scheduling facilitate visual management.

Despite the high number of interactions that are of significance importance, the participants reported some negative interactions that arisen by integration of BIM and LC.

“Rapid generation and evaluation of construction plan alternatives” have negative interaction with “reduce cycle times”. Reduction of cycle times is about reduction of production cycle durations and reduction of inventory. Rapid generation of construction plan alternatives increase inventory of designs. This functionality also complicates rather than simplifying the design by adding detailed planning and design. “Online/electronic object-based communication” and “design the production system for flow and value” have a negative interaction. Design the production system for flow and value requires applications of reliable technology, however, BIM is not mature yet.

By presenting positive interactions achieved by implementing both BIM and LC in the construction industry as well as the weak interactions, this study can be conducted in a country-by-country basis. Moreover, a construction case study can be carried out by implementing functionalities and principles suggested in this research. For further research, structural equation modelling (SEM) can be used to analyse between variables and latent constructs. The results of this study have contributed and strengthened the BIM and LC body of knowledge by suggesting positive and negative interactions. The outcome of the thesis proposes solid interactions for adoption of BIM and LC. This would also act as a reference for the construction firms, stakeholders of the construction projects for integration of BIM and LC.



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APPENDICES

APPENDIX A: Explanations for Interaction Matrix of Lean Principles and BIM Functionalities

APPENDIX B: Survey for BIM and LC Interaction: A Delphi Method



APPENDIX A

Table A.1 : Matrix Interaction: Cell contents' explanations (Sacks et al, 2010).

Index	Explanations	Author
1	A close to real and rendered design in the early stage of a project, and assessment of the design against performance requirements such as energy, acoustics, wind and thermal propose a quality end product and in alignment with the intended design. The design more realistic for non technical stakeholders, thus value defined from client perspectives and demands are met. This functionality reduces the variability that incurred due the late-client initiated changes during construction stage.	(Eastman et al, 2008; Manning and Messner, 2008)
2	BIM allows clash checking and automated checking that enable the designers to easily detect flaws or any other defects. As a result, the quality is improved, "making-do" is inhibited, and finally rework is reduced.	(Dehlin and Olofsson 2008; Eastman et al, 2008)
3	With increase in building complexity, BIM simplifies understanding of complex system with visualisation.	(Eastman et al, 2008)
4	3D modelling with a realistic model provides the client with comprehensive understanding of the end product compared to 2D drawings. Therefore, client and other stakeholders are involved in the decision-making for intended design.	(Eastman et al, 2008; Manning and Messner, 2008)
5	A more efficient design validation and verification of design against the specification and regulation are enabled by BIM with the intelligence existence in the model objects.	(Eastman et al, 2008; Khanzode et al, 2008)
6	Virtual reality facilitates the managers to visit the construction site virtually compared to the report and hearsay by others.	(Whyte, 2002)
7	BIM enables to reuse models and see the design change impacts and allow fast manipulation of design.	(Eastman et al, 2008)
8	Multiskilled teams will perform the tasks concurrently for multiple design alternatives which will minimize the design change. Moreover, multiple design gives the flexibility to run performance analysis such as cost estimation, project planning and drawings.	(Eastman et al. 2008; Khemlani, 2009)
9	Checking the proposed design against the performance criteria guarantee that the design serves the intended function thus reducing the variability and improve the value for the client.	(Eastman et al, 2008)
10	Automated quantity takeoff prevents human error and also automatically do the quantity takeoff when there is any change in the design; hence, it enhances flow by reducing variability.	(Eastman et al, 2008)

Table A.1 (Continued): Matrix Interaction: Cell contents' explanations (Sacks et al, 2010).

11	BIM ensures a single information model that all stakeholders have access to and the consistency is maintained through out the project lifecycle compared to 2D drawings that onjects are saved in various places.	(Eastman et al, 2008)
12	Software such as Solibri, Navisworks, and Tekla do clash detection and checking through iterative process, thus lead to flawless and complete on-site implementation.	(Eastman et al, 2008)
13	Automated and multidisciplinary clash checking and other design issue in the early stage of design expose design problems.	(Eastman et al, 2008; Khanzode et al, 2008)
14	Automation of task gerneration for planning results in an error-free gereneration of tasks.	(Eastman et al, 2008)
15	Discrete event simulation is used for production process enhancement by virtual first-run studies.	(Eastman et al, 2008)
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 multiobjective optimization procedures such as genetic algorithms.	(Eastman et al, 2008)
17	Simulation of production and and manual for installation can be prepared. This will ensure standardized procedures for high turnover rate of construction industry.	(Eastman et al, 2008)
18	Up-to-date information online, enables identification of conflicts and errors and mitigates their impact.	(Eastman et al, 2008;
19	Automated steel or rebar fabrication machinery eliminates errors incurred by human.	Khanzode et al, 2008)
20	Online access of information eliminates waiting time and therefore, enhancing flow.	(Khemlani, 2009)
21	Activation of bar codes scanning enable precise and fast reporting.	(Vela, 2009)
22	Fast structural, thermal and acoustic analyses, cost estimation and requirements capture collapse cycle time.	(Eastman et al, 2008)
23	Coordination of designer and parallel processing shorten the cycle time.	(Khemlani, 2009)
24	Automated and model-based coordination among disciplines reduce cycle time.	(Eastman et al, 2008)
25	Automated cost estimation, performance analysis, and study of compliance with client need reduce cycle time.	
26	BIM model visualises the process such as KanBIM which shortens cycle times.	(Sacks et al, 2010)

Table A.1 (Continued): Matrix Interaction: Cell contents' explanations (Sacks et al, 2010).

27	Computer-controlled machinery fed from a model will do intensive labor work thus will reduce cycle times.	(Eastman et al, 2008)
28	Cycle times are reduced by eliminating data processing steps for order of materials.	(Vela, 2009)
29	This increases the inventory of design alternatives which gives the client a good opportunity for choosing best option.	(Khemlani, 2009)
30	Online visualisation helps conduct production strategies designed for reduction of work-in-progress inventories and production batch sizes.	(Sacks et al, 2009)
31	Automated generation of new task reduces set up time.	(Eastman et al, 2008)
32	Automated data entry eliminates set up time.	(Tekla, 2009b)
33	Application of an integrated model and design coordination among designer teams enable a collaborative work environment that can share their knowledge in a parallel process.	(Khanzode et al, 2006; Liston et al, 2001)
34	Process visualisation and online communication allow sequencing and lookahead planning of work packages that is enabled by last palnner system.	(Sacks et al, 2009)
35	Integration of BIM systems with supplier's database improve communication and enable pull production.	(Vela, 2009)
36	BIM allows serveral users to work on a shared model synchronously, which enables sharing of tasks between users	Not yet available
37	Discrete event simulation uncovers unbalanced work allocations.	(Li et al, 2009)
38	Access to online product data, company protocols, and production requirements improve standardisation work practice.	(Hewage and Ruwanpura, 2009; Sacks et al, 2010; Sriprasert and Dawood, 2003)
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.	Not yet available
40	BIM-enabled visualisation throughout the project desgin and construction stage such as 3D, 4D for construction processes which all contribute to process optimization and improve flow.	(Eastman et al, 2008; Li et al, 2009)
41	Detailed planning will increase complexity rather than simplifying.	Not yet available
42	These applications cannot be considered mature technology.	(Manning and Messner, 2008)

Table A.1 (Continued): Matrix Interaction: Cell contents' explanations (Sacks et al, 2010).

43	A 3D model gives a realistic prototype of end product and permit the end users to interact with designers will enable the designer to capture the intent requirements.	(Eastman et al, 2008)
44	Fast creation of production plan alternatives enables a set-based approach to production system and production planning.	(Kong and Li, 2009)
45	Online access provides the most up-to-date design information to all stakeholders.	(Hewage and Ruwanpura, 2009)
46	Solving integration issues of various disciplines and clash checking verify and validate the product information.	(Li et al, 2009)
47	Visualisation of planned schedule and current processes verify and validate the process information.	(Dehlin and Olofsson, 2008)
48	This functionality enables the managers to see real-time digital twin of project on their screen.	(Sacks et al, 2009)
49	This function gives better information to all stakeholder for decision making.	(Dehlin and Olofsson, 2008)
50	Integration of different companies' logistics enables these companies to cooperate together.	Not yet available
51	use of design models for performance analysis reduce setup time.	Not yet available
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.	Not yet available
53	Automated generation of drawings, enables production of smaller batches since provide us with on demand information	Not yet available
54	Automated drawing generation improves engineering capacity when compared with 2D drafting, and it is a more reliable technology because it produces properly coordinated drawing sets.	(Sacks and Barak, 2008; Tekla, 2009a)
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.	(Dehlin and Olofsson, 2008)
56	Access of all stakeholders to models improve communication and confirm that the design requirements are met and understood.	Not yet available

APPENDIX B

BIM and LC Interaction: A Delphi Method

This survey is part of an MSc thesis examining the interaction of "Building Information Modeling" (BIM) and "Lean Construction" (LC) within the architecture, engineering and construction (AEC) industry. The main purpose of the survey is to determine the current state of the art in BIM and LC interaction.

All information will be used for the purpose of research only. Individual respondents and companies will not be identified.

Thank you for your time. Please do not hesitate to contact me, Abdul Hamid Eshaqzada at eshaqzada18@itu.edu.tr or Bahriye Ilhan at ilhanba@itu.edu.tr.

* Required

1. Your name and surname? *

2. What is the highest degree you have completed? *

Mark only one oval.

- ☐ Bachelor's degree
☐ Master's degree
☐ Doctorate degree
☐ I am studying for my master degree.
☐ I am studying for my PhD
☐ Other: _____

3. What is your field of study? *

Mark only one oval.

- ☐ Architecture
☐ Civil Engineering
☐ Electrical Draftsman
☐ Other: _____

4. What is your role in the company? *

5. Do you use BIM or Lean Construction In your company? *

Mark only one oval.

- ☐ Yes
☐ No

6. How many years of experience in the BIM and/or LC fields? *

Mark only one oval.

- ☐ Less than 2 years
☐ 2-5 years
☐ 6-10 years
☐ 11-15 years
☐ 16+ years

Brief on Delphi Method

The Delphi method is a structured method for forecasting with reliance on judgement of experts (Brown et al, 1968). The Delphi method is an iterative process and it elicits and distills anonymous judgements of experts without direct confrontation. Traditionally, experts have been discussing to reach a group solution to a problem but psychological factors such as persuasive personality, conformity, presence of dominant, unwillingness to change publicly expressed opinion have undermined this approach. Therefore, this survey aims to extract experts judgement on "Interaction of BIM and LC".

7. In the following checkbox grid, Lean principles are listed in the row while BIM functionalities are listed in the column (Sacks et al, 2010). Based on your experience please indicate which BIM functionalities support which Lean Principles and vice versa.

Please see the following link for detailed descriptions for Lean Principles and BIM functionalities: <https://docs.google.com/spreadsheets/d/1cWnPAuTj6hXmWnv99k37-GaPyX8Fs0eFJeBJ0exBQ6g/edit?usp=sharing>

Check all that apply.

	Visualization of form	Rapid generation of multiple design alternatives	Reuse of model data for predictive analyses	Maintenance of information and design model integrity	Automated generation of drawings and documents	Collaboration in design and construction	Institute continuous improvement	Online/electronic object-based communication
Reduce variability	☐	☐	☐	☐	☐	☐	☐	☐
Reduce cycle times	☐	☐	☐	☐	☐	☐	☐	☐
Reduce batch sizes (strive for single piece flow)	☐	☐	☐	☐	☐	☐	☐	☐
Increase flexibility	☐	☐	☐	☐	☐	☐	☐	☐
Select an appropriate production control approach	☐	☐	☐	☐	☐	☐	☐	☐
Standardize	☐	☐	☐	☐	☐	☐	☐	☐
Institute continuous improvement	☐	☐	☐	☐	☐	☐	☐	☐
Use visual management	☐	☐	☐	☐	☐	☐	☐	☐
Design the production system for flow and value	☐	☐	☐	☐	☐	☐	☐	☐
Ensure comprehensive requirement capture	☐	☐	☐	☐	☐	☐	☐	☐
Focus on concept selection	☐	☐	☐	☐	☐	☐	☐	☐
Ensure requirement flow down	☐	☐	☐	☐	☐	☐	☐	☐
Verify and validate	☐	☐	☐	☐	☐	☐	☐	☐
Go and see for yourself	☐	☐	☐	☐	☐	☐	☐	☐
Decide by consensus, consider all options	☐	☐	☐	☐	☐	☐	☐	☐
Cultivate an extended network of partners	☐	☐	☐	☐	☐	☐	☐	☐

8. Your commentary regarding the interaction of BIM and LC is appreciated if there is any.

This content is neither created nor endorsed by Google.

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Figure B.1: Survey for BIM and LC Interaction: A Delphi Method

EDUCATION

:

- **B.Sc.** : 2018, Boğaziçi University, Engineering Faculty, Civil Engineering

PROFESSIONAL EXPERIENCE AND REWARDS:

- **Kuzu Group, Finance Intern**
 - Worked as cost and finance engineer at SeaPearl Jumeirah Hotel in Ataköy, Istanbul.
 - Prepared quantity take-off for reinforcement, concrete, mold, plaster.
 - Made monthly payment progress for more than 10 subcontractors for payment.
 - Prepared monthly report to the project manager and my supervisor.
- **Göçay Construction Contracting and Trade Co. Inc., Site and Road Engineer Intern**
 - Supervised highway construction such as pile foundation, viaduct, bridge, underpass, box culvert and asphalt.
 - Involved in supervision of viaduct footings and piers, drilling.
 - Worked in laboratory and conducted tests such as sieve analysis, marshall stability test, methylene blue test, asphalt quality control test, California bearing ratio test, cone test.
 - Monitored earthworks, haul, stability test, subgrade and base course layers.
- **International Catholic Migration Commission (ICMC), Interpreter (English-Persian)**
 - The ICMC Resettlement Support Center for Turkey and the Middle East is a long-standing partner of the U.S. Refugee Admissions Program.

- Provide interpreting services for three main departments at ICMC: US Department of Homeland Security (DHS), Pre-screening and Cultural Orientation (CO).

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Eshaqzada, A. H. and Ilhan Jones, B.** (2020). Interaction of Building Information Modelling (BIM) and Lean Construction: A Bibliometric Analysis, International Project and Construction Management Conference, 906-915.
- **Abdul Hamid Eshaqzada**, “Design of Floating Units as Post Earthquake Temporary Housing for Istanbul”, Bachelor’s Thesis Project, Prof. Dr. Emre Otay.

