A Quantitative, Evidence-based Analysis of Correlations Between Lean Construction and Building Information Modelling

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ABSTRACT

Purpose: This research aims to identify and measure the correlations between Building Information Modelling (BIM) and Lean Construction (LC) principles at the design and construction phases.

Design/methodology/approach: The study investigates BIM-LC principles correlations using the Istanbul Grant Airport (IGA) as a case study. The Delphi technique, performed quantitatively, contributes to the identification and quantification of a set of correlations between 11 selected BIM uses and 13 LC principles, which are supported with practical examples from the case study.

Findings: Together, the two research methods provide an evidence-based approach to understand the correlations between BIM and LC. The correlation analysis results in 46 correlations, and the correlations between the LC principles and BIM uses are intensified with the LC principles.

Originality: BIM and LC practices represent approaches to improve performance in construction projects. While BIM has both information technology (IT) and process perspectives, the LC approach is mainly a process and product-oriented philosophy for project efficiency, effectiveness and the elimination of non-value-adding activities and waste. Many studies have investigated how the two approaches complement each other and concluded that their combined implementation in projects can improve efficiency and effectiveness. However, to date an analytical and granular investigation identifying and measuring correlations between BIM and LC based on empirical data is lacking. This paper fills that gap with an evidence-based analysis of the tightness of coupling and correlations between BIM uses and LC principles.

Practical implications: A quantitative understanding BIM use and LC principles correlations and appreciation of their specific uses can guide the practical implementation of BIM and LC, especially in large and mega projects.

Keywords: Building Information Modelling (BIM), Lean Construction (LC) principles, Delphi study, airport construction project, evidential analysis, correlations.

1. INTRODUCTION

Lean construction (LC) and building information modelling (BIM) are recognised as two key approaches for improving performance and productivity in the construction industry. Together, they provide a number of tools and methods for improving the production processes and information management workflows (Ningappa, 2011; Sacks et al., 2010). Although each (BIM and LC) has a different perspective to address the problem domain, their goal and purposes within construction projects are aligned (Khodeir and Othman, 2018). This alignment has been the subject of several research studies aiming to identify synergies and overlaps.

Delivering projects to quality and budget targets through the effective management of human and material resources, reduction in waste, and collaborative ways of working is crucial in the construction sector (Akinade and Oyedele, 2019). In achieving these benefits, LC and BIM are applied separately, yet their similarities and overlapping benefits make them attractive for simultaneous application, which may provide efficiency and efficacy gains beyond those achievable through their individual application (Rosayuru et al., 2019).

BIM is alleged to reduce waste, minimise delays, resolve safety-related problems, improve project schedules, detect clashes during the design stage, reduce construction costs and improve communication and facility management (BSI, 2019; Eastman, Teicholz, Sacks and Liston, 2008; NIMBS Committee, 2007; Utkucu and Sozer, 2020). Xing et al. (2021) found that BIM facilitates clear visual presentations of design schemes, changes in projects and construction simulations.

The LC approach aims to address similar challenges, such as minimising waste and maximising the value to clients. When LC is applied in isolation, it is often challenged by barriers such as poor communication and collaboration and lack of transparency (Enshassi et al., 2019), which are considered as among the key characteristics of BIM processes. This has led to the view that the simultaneous implementation of BIM and LC is a key trend for the future of the construction sector (Koseoglu and Gunes, 2018; Nascimento et al., 2018). To date, however, the synergies between BIM and LC have only been explored in a qualitative way. This is likely to be a result of challenges that have prohibited the quantification of evidence about the relevant correlations, such as the dearth of projects available to scholars and implementing both LC and BIM. Mahmood and Abrishami (2020) investigated the synergies between BIM and LC for building surveying practices, and Herrera et al. (2021) measured associations between LC practices and BIM uses for the planning and design phases.

In the light of advances in the literature, a quantitative analysis of the synergies between BIM and LC for the construction phase is a gap that needs addressing for the practical implications of BIM and LC implementation in construction management. This study thus aims to provide a quantitative evidential analysis of synergies between BIM use cases and LC principles using a case study approach, namely, the Istanbul Grant Airport (IGA) project.

First, a critical review of BIM and LC concepts and interrogation of cutting-edge research published in the literature are provided to build the baseline for the research developed here. Then, the research methodology is explained at theoretical and empirical levels. This is followed by the identification of 13 LC principles via the literature and explanation of 11 BIM uses in the IGA project. After that, a Delphi study is implemented for the analysis and measurement of the correlation between the LC principles and BIM uses. LC gains from the BIM uses due to the measured correlations are then discussed before concluding.

2. RELATED STUDIES

LC and BIM are considered as independent from each other (i.e., LC practices can be adopted without BIM, and BIM can be adopted without LC) (Sacks et al., 2010). However, they both contribute to project outputs by reducing waste and increasing value and quality (Dave et al., 2013). The two main goals of LC in relation to productivity and performance improvement during construction are to minimise physical and process waste and to improve value generation for the client (Dave et al, 2013). More broadly, LC improves communication among the parties in a project (Daniel and Pasquire, 2019), which extends its value from economic gains to broader areas, such as an understanding of the various stakeholder positions.

Studies of BIM and LC show a correlation between them when this has only been explored in general terms. The process and product elements of LC and BIM were investigated by Khanzode et al. (2008) at the design stage in a case study project; Sacks et al. (2009) proposed two prototypes for process visualisation and construction visualisation focusing on safety planning and workers coordination. Gerber et al. (2010) conducted three case studies, mapped the outcomes and concluded that BIM would become increasingly essential and linked to LC practices in design and construction management. Kjartansdóttir (2011) investigated possible joint applications of BIM and LC within the Icelandic construction industry and found such cases to be scarce. Focussing on the Internet of Things (IoT) and LC, Dave et al. (2015) concluded such emerging LC management systems such as visual LC (VisiLean) and Kanban systems for BIM (KanBIM) can be enhanced using IoT in reporting site status through real-time feedback loops. Using a hospital building case study and a set of project metrics, Zhang (et al. 2018) concluded that BIM can be used to achieve LC principles. However, no direct or quantitative correlation analyses between specific BIM uses and LC principles were performed.

Dakhil et al. (2019) studied the factors involved in successful BIM adoption by clients and their impact on delivering value to clients in BIM-enabled projects and found BIM vision, skills and standards to be very important. Based on a systematic review of 215 journal papers published between 2001 and 2018, Mellado and Lou (2020) developed a framework for the integration of BIM, LC and sustainability to show the synergies between these concepts. This study also confirmed the potential synergy between the two concepts. Evans et al. (2020) studied critical success factors for the adoption of BIM and LC on mega construction projects and identified 'collaboration in design, construction works and engineering management' as the most critical success factor for achieving BIM-LC synergy. In a subsequent study, Evans and Farrell (2021) explored BIM and LC integration barriers in mega projects and determined a list of critical barriers to BIM-LC integration.

Aslam et al. (2021) investigated the integrated implementation of virtual design and construction (VDC) with a LC project delivery system by performing a systematic literature review. They identified a total of 351 hypothetical interactions and 65 opportunities, but these were largely hypothetical and not tested. Sepasgozar et al. (2021) performed a systematic review of BIM studies for LC purposes to study potential synergies between the two. Their findings confirmed the synergy between BIM and LC practices and anticipated that such synergies would develop in construction with the application of Digital Twin. They also provided a significant literature review of BIM and LC synergies and confirmed the gap in terms of the lack of evidence-based quantitative evaluation.

In a similar study, Mahmood and Abrishami (2020) investigated the effect of BIM on LC practices using a questionnaire and correlation analysis techniques to study associations between eight preselected and fixed BIM functionalities and eight LC principles. However, this study was confined to building surveying practices. Herrera et al. (2021) analysed associations between LC practices and BIM uses during the planning and design phases with data gathered from 64 projects. They identified 33 relationships between BIM used and LC design management (LDM) principles and again concluded that the implementation of BIM uses and LDM practices are still at a nascent stage (here, at the design phase). Mellado and Lou (2020) also concurred with this conclusion regarding the nascent nature of the challenge of identifying quantitative and practice-based evidence relationships for BIM-LC correlations and argued that are still benefits to be untapped from their synergy. A tabulated list of this literature is given in Table 1.

Table 1: Literature studies on BIM and LC

Aim of the paper	Case study	Reference
Introduction of novel computer-aided process visualisation tool for work progress and safety planning	√	Sacks (et al. 2009)
Analysis and exploration of the relation of BIM and LC	√	Gerber et al. (2010)
Analysis of BIM and LC implementation level within the Icelandic construction industry	x	Kjartansdóttir (2011)
Improvement of LC practices VisiLean and KanBIM with IoT	x	Dave et al. (2015)
Contribution of BIM use to achieve LC	√	Zhang (et al. 2018)
Investigation of the synergy between BIM and LC practices for building surveying practices	x	Mahmood and Abrishami (2020)
Development of a framework for the integration of BIM, LC and sustainability by articulating existing works	x	Mellado and Lou (2020)
Determination of critical success factors for the adoption of BIM and LC on mega construction projects	x	Evans et al. (2020)
BIM and LC integration barriers in mega projects	x	Evans and Farrell (2021)
Investigation of VDC implementations in LC project delivery systems	x	Aslam et al. (2021)
Implementing systematic review of BIM studies for LC purposes focusing on IoT applications	x	Sepasgozar et al. (2021)
Identification of associations between LC practices and BIM uses during planning and design phases	√	Herrera et al. (2021)

The present study contributes to this domain by investigating the degree of correlations between BIM uses and LC principles through a granular and evidence-based analysis in a real-world project where both BIM and LC principles were adopted.

3. RESEARCH METHODOLOGY

This study adopts an analytical approach to investigating the correlations between BIM and the LC principles using the IGA project as a real-world project. The approach utilises existing knowledge about the BIM and LC synergies identified in the literature and augments them through a quantitative analysis of the correlations between BIM uses and LC principles. The overarching aim is to contribute to filling the identified knowledge gap through a project-based evidential analysis of BIM and LC correlations.

The ontological position of this research is mainly objectivist, as it acknowledges that BIM and LC interactions exist independently from the observers/researchers involved in this research paper. Although its epistemology, under the ontologically objectivist stance, is mainly positivist (i.e., true findings about BIM-LC interactions can be identified using a quantitative approach), it also has an element of subjectivism in acknowledging the constructive nature of the BIM-LC interactions that the industry experts involved in the study are likely to have. The Delphi method is used to identify the BIM-LC correlations.

Delphi is often used when a data collection procedure is difficult, when there is not much empirical evidence, when research requires access to sensitive data (Hallowell and Gambatese, 2010), or when experimental research is unrealistic (Ameyaw et al., 2016). Although other methods and techniques, such as survey and brainstorming techniques, can be used to collect subjective data, controlling the individual bias of respondents with such techniques tends to be challenging (Hallowell and Gambatese, 2010). Reliability issues can be encountered in the design and execution of the Delphi method also, related to issues such as an inadequate selection of survey items, the choice of experts, moderator bias and unreliable analysis and feedback. The Delphi method is considered a qualitative method in some sources, although it can be used quantitatively with the addition of statistical data analysis and other advanced modelling methods, such as analytical hierarchy process (AHP) and fuzzy sets (Ameyaw et al., 2016).

Several construction management studies have used Delphi, including to select a project procurement method in contracting studies (Ameyaw et al., 2016); to identify the benefits of BIM-LC through two rounds of questionnaires with ten experts (Seyis, 2017); to investigate BIM assisted green building certification process (Liu et al., 2017); to identify knowledge, skills, and abilities that need to be included BIM body of knowledge framework (Wu et al., 2018); to examine the critical barriers for the integration of BIM and LC in large projects (Evans and Farrell, 2020); and to determine weights and key trends for construction supply chain management, and evaluate the weights of LC tools with 16 experts (Le and Nguyen, 2021).

The research methods, as shown in Figure 1, employed to investigate the BIM-LC correlations reflect this epistemological stance. The research approach is mainly inductive because it starts with general concepts about the BIM-LC interactions but without prior consideration of any specific BIM and LC interactions.

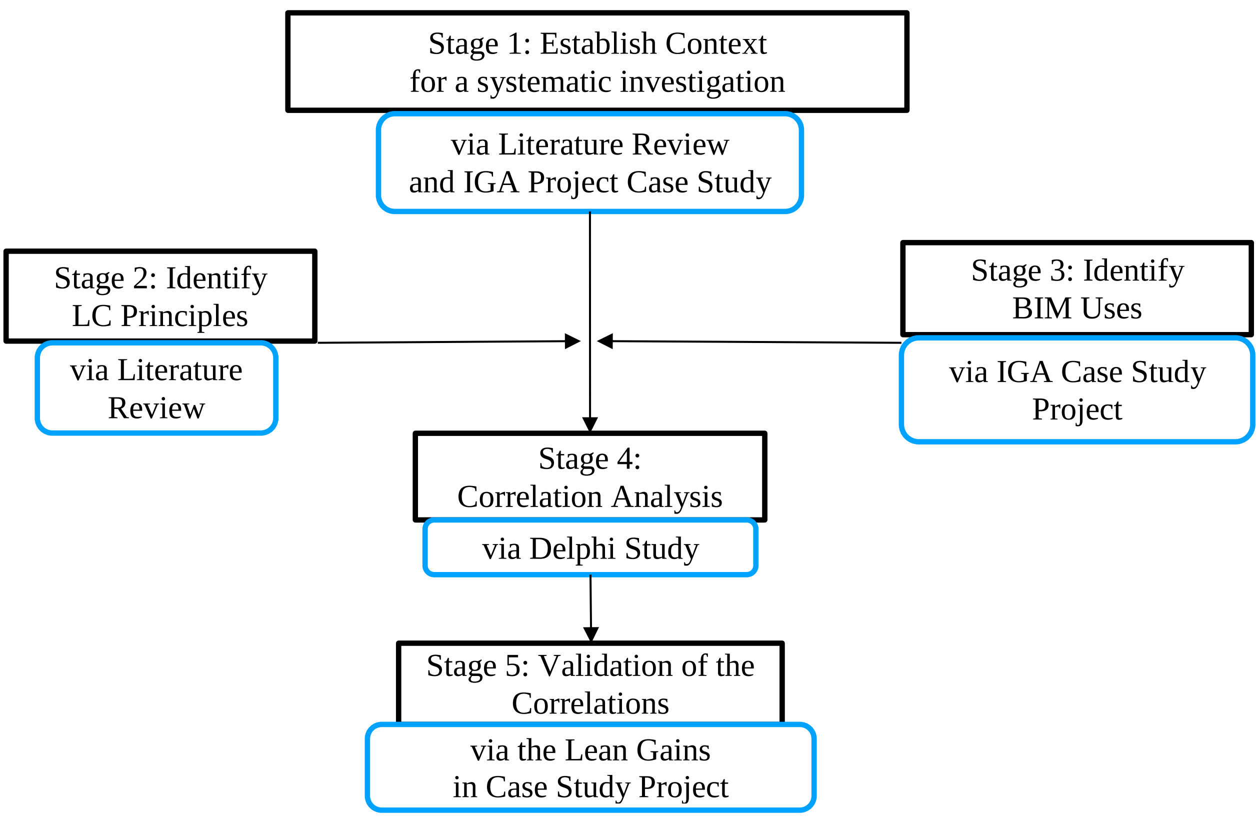

Fig. 1. Research process plan.

The LC principles are obtained from the literature review. The BIM uses were those adopted in the IGA project. These were also observed from a construction management perspective to verify their LC effect to triangulate the quantitative results of correlations identified by the Delphi method with the experts.

The IGA project was a highly complex, large-scale project that involved many international and local companies in design and construction. It had four phases, the first including the construction of three runways, an air traffic control ATC) tower, a terminal with five piers covering an area of 1.3 million m^2 (14 million square feet) and a car park of 700,000 m^2 (7.5 million square feet). The other site facilities included icing areas, cargo facilities, rescue and fire station, fuel farm and wastewater treatment plant, a Geographical Information System (GIS) centre and utilities centre.

As shown in Figure 1, the research consisted of several stages. Stage 1 developed the context for a systematic investigation by identifying the existing knowledge available on BIM-LC interactions and evidencing the absence of quantitative and evidence-based approaches to the problem. Stage 2 identified the key LC principles from the literature. These are explained in the next section and were used to begin the qualitative investigation of the LC efficiency gains vis-a-vis the BIM uses implemented in the IGA project. This enabled a systematic and quantitative evaluation of the correlations between BIM and LC with ten key personnel involved in the IGA project (Stage 3). The selected participants all had working experience with BIM and LC (participant profiles are given in Tables 2 and 3). A Delphi study was used to match and measure the correlation between BIM and LC for design and construction management (Stage 4). The product of the Delphi exercise was a matrix showing the correlation between BIM uses and LC principles, which was then examined and discussed in relation to 1) the LC gains achieved in the project for validation and 2) its potential contribution in devising a model for organisation and project decision-makers selecting LC and BIM capabilities (Stage 5).

4. LC PRINCIPLES

The LC concept is a management/production philosophy on enhancing productivity and quality for clients while managing project resources, including human, equipment and time and space resources. LC enables the execution of intended work at the right time, place and amount while reducing waste and enabling flexibility and openness to change. LC processes have evolved over the years and are now recognised as offering an effective project management and control approach in construction projects (Redeker et al., 2019; Sommer and Blumenthal, 2019). LC principles, adapted from Sacks et al. (2010), are listed in Table 2.

Table 2: LC Principles: the industry perspective (adapted from Sacks et al. 2010)

LC Principles	Granulated LC Principles
Improve flow processes via	L1: Reduce variability in product characteristics L2: Reduce production cycle time (design, construction, material logistics) L3: Increase flexibility by simplifying the production systems L4: Learn and systematically develop for continuous improvement L5: Use visual management for process flow, improving compliance and continuous improvement L6: Focus on flow and value generation in the production system via simplification of the process, synchronisation of processes and use of reliable means/technologies.

Value generation process	L7: Ensure comprehensive requirements capture L8: Focus on concept selection L9: Ensure requirements flow down L10: Verify and validate
Problem-solving	L11: Go and see yourself L12: Decide by consensus, consider all options
Developing partners	L13: Cultivate an extended network of partners

The construction industry has its own characteristics that require the adaptation of the LC principles and methods borne within the manufacturing industry. It is characterised by temporary multi-party organisations, uncoupled supply chains and project delivery systems, considerable regulatory intervention, and a multitude of specialised trades. Projects in such environments are regularly challenged by unpredictable outcomes impacted by frequent time and space conflicts, regular claims and disputes and inadequate collaboration (Tezel et al., 2018). While LC principles cannot address all the underlying challenges within the construction industry, they have proven their ability to address some of the key issues affecting productivity at the workplace, such as reducing waste and improving communication and quality (Jeong and Yoon, 2016).

5. BIM USES IN IGA PROJECT

BIM uses (BUs) were captured from the IGA project. This implemented a variety of BIM uses that evolved through the project lifecycle, integrating people, systems, control and communication. The highly collaborative and well-documented BIM approach adopted facilitated the capture of implicit knowledge and experience of participants. Core BIM functionalities used in the project are given below.

BU1: Collaborative BIM design coordination

Collaborative design coordination is a BIM-enabled process that helps in monitoring the progress of the design and exchange of information. This process was supported by a virtual cloud-based environment sharing project information. For example, Figure 2 shows a small part of the terminal building model, with one of the piers from which passengers go to the gates for planes circled. The size of the BIM model utilised for collaborative design coordination was about 17 GB.

Fig. 2. Design coordination in the IGA terminal piers construction

The main contractor had a dedicated BIM department that managed the communication and design coordination between design and engineering firms responsible for the structure, architecture, mechanical, electrical, and plumbing (MEP) and baggage handling systems.

BU2: BIM visualisation for communicating project intent

Given the complexity of the project, visualisation was key to improving the project parties' understanding of the design and construction (Figure 3). This was especially important to the construction phase and coordinating the design processes.

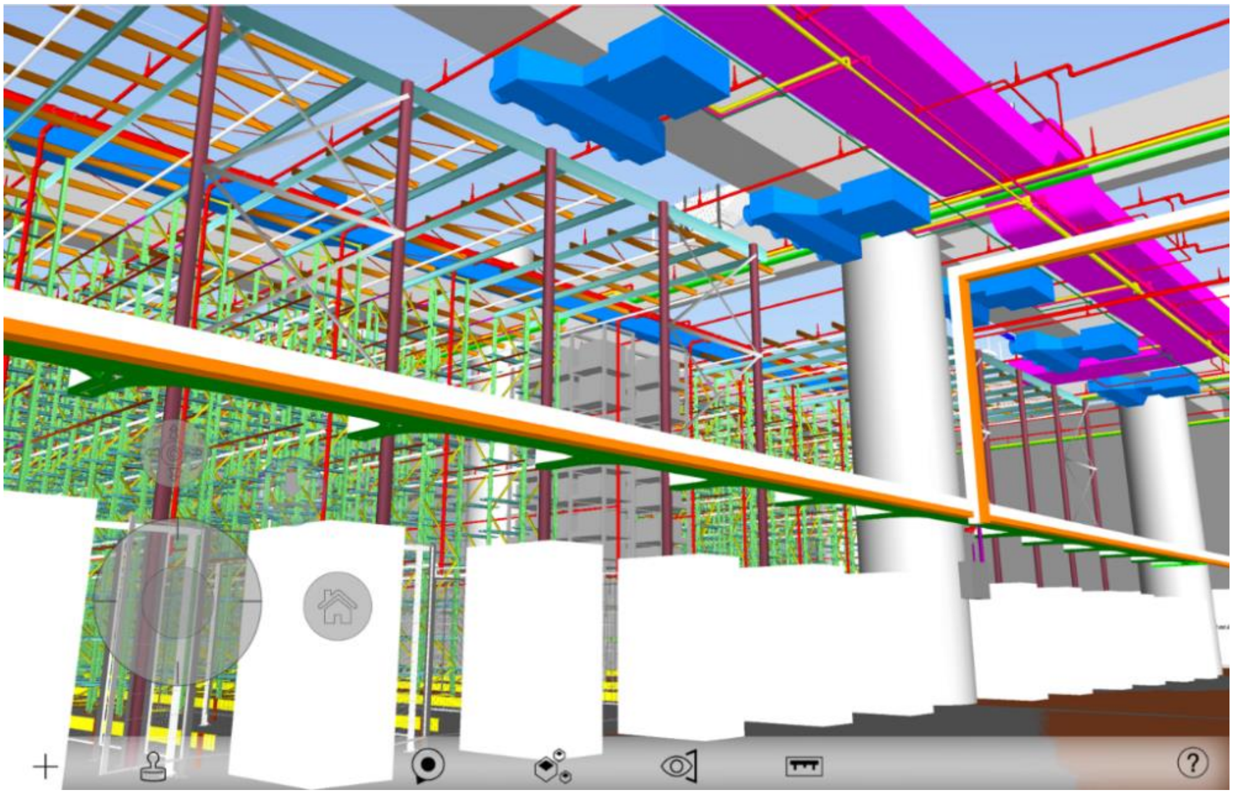

Fig. 3. Visualisation with BIM in the IGA terminal building construction

BIM had a critical role in improving the efficiency of the design and construction processes. For example, 3D snapshots of the key assets and zones were shared every week from the 4D BIM model and used for decision-making by the relevant project parties to coordinate site activities and their required resources.

BU3: BIM-based buildability assessment

Buildability was another key challenge in the face of various constraints (related to relationships among the IGA systems, space, sequence, etc.). Model-based buildability review meetings were regularly held to study design and construction options from the buildability perspective prior to issuing the shop drawings and other construction documents to the site.

These construction documents were also shared with the site team through cloud-based applications to inform installation activities onsite using the 4D BIM model shown in Figure 4 (which shows an integrated 4D BIM model with more than 30,000 construction activities). This was developed and used regularly to monitor both design and construction progress.

This process helped the teams to examine buildability challenges and design validation daily before the shop drawings were produced, which helped to avoid any possible rework on site.

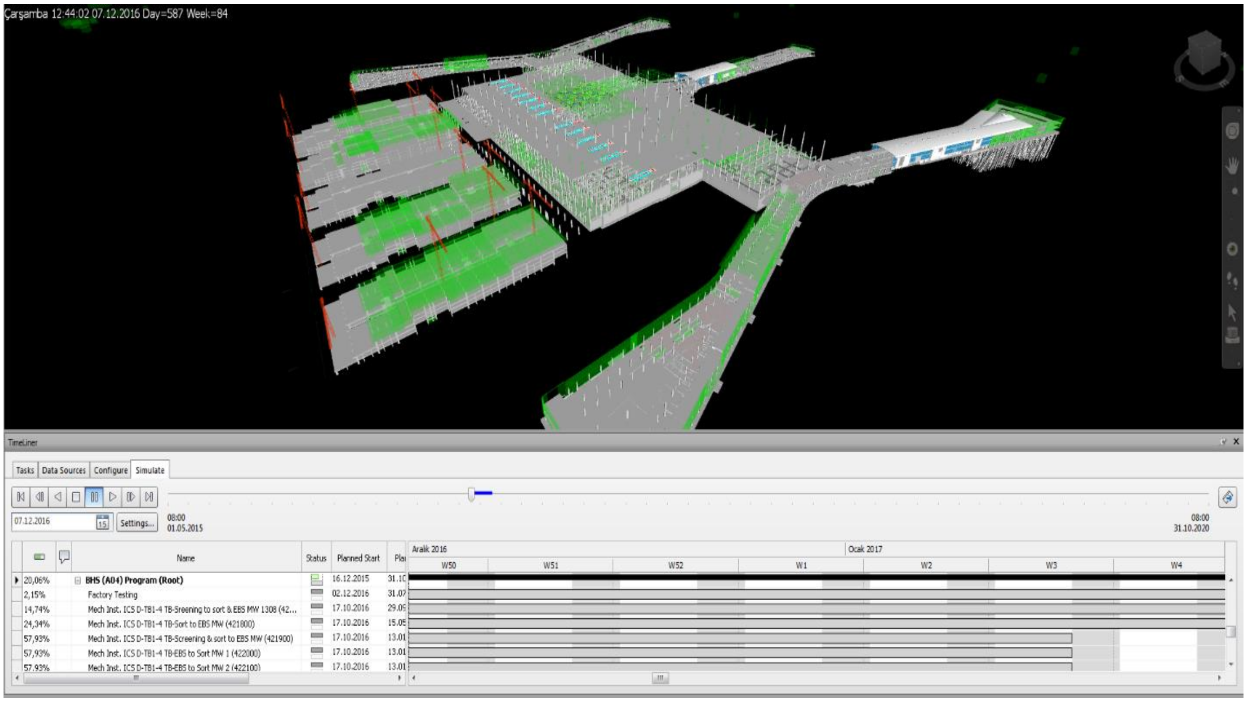

Fig. 4. Cross-checked BIM model delivered to the site in the IGA terminal building with piers.

BU4: BIM-based conflict detection and clash avoidance

All the disciplines, including architectural, structural and MEP, were combined to detect and resolve clashes. A comprehensive clash avoidance process can help to identify both major and minor conflicts at the design stage. BIM information managers were then able to hold meetings with the related stakeholders to resolve the identified clashes and identify how design actions could be coordinated to finalise the clash resolution. Clash reports documented the comments and resolution advice for faster clash resolution.

Model elements were managed through selection sets based on discipline key/critical areas according to asset, discipline, level and zone. This process helped the project team to diagnose design errors before construction on site. The corrections/revisions were applied directly to the BIM models. The consequences of the corrective actions were closely monitored and shared with the relevant parties. Figure 5 shows an example of a superimposed BIM model of mechanical and structural systems.

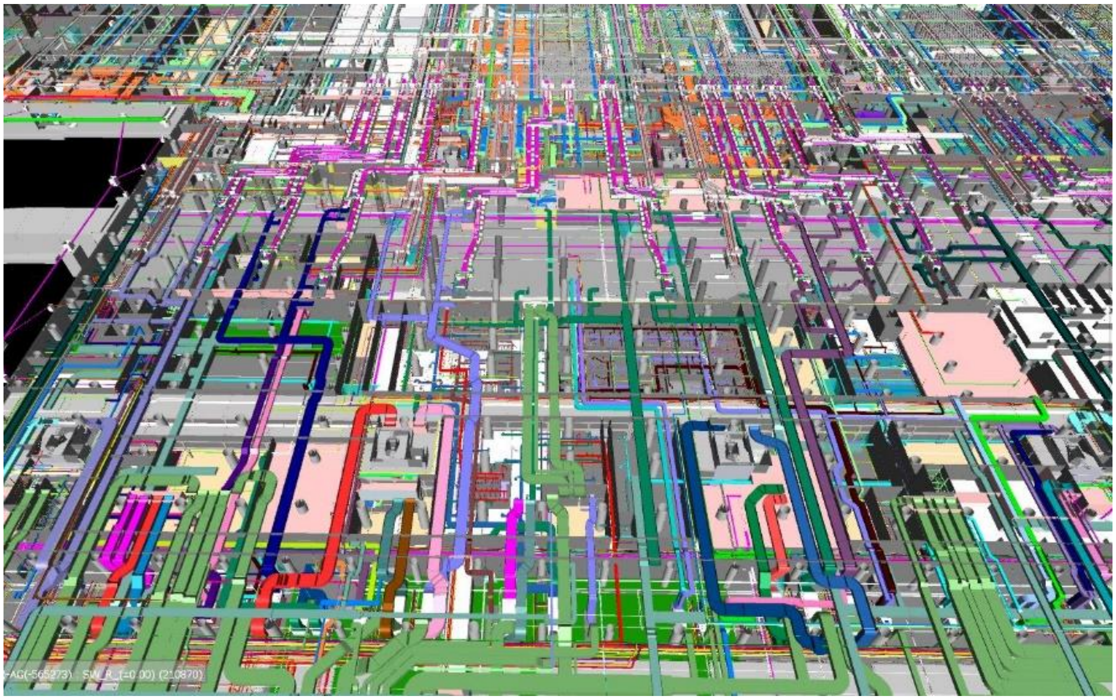

Fig. 5. A view of a clash analysis: mechanical and structural systems in IGA terminal building design

BU5: Scheduling and progress monitoring with 4D BIM

Accurate sequencing and planning of look-ahead work was crucial for this complex mega project. Hence, a significant part of the BIM use was the 4D BIM employed to support scheduling. 4D BIM models supported the master scheduling. Information from mobile BIM technologies used onsite by engineers and surveyors was utilised to visualise the model and update the records of the building model for progress monitoring in real-time (Figure 6).

Fig. 6. Real-time progress monitoring and engineering surveying in IGA construction site

For example, 4D BIM modelling helped to produce accurate two-weekly look-ahead scheduling for planning and production (Figure 7). The Master Schedule of the project had thousands of tasks. Meeting the challenge of transferring this information to the execution level and updating it with the accomplished tasks accurately was possible with 4D BIM.

Project Name: Date: 1.Tem.16

Project Manager: Project Phase: Level 1-Stage 1-Plum

Schedule ID	Construction Activity	Duration	M	T	W	TH	F	SA	S	M	T	W	TH	F	SA	S	% Completion	Resources	Comments
			1	2	3	4	5	6	7	8	9	10	11	12	13	14			
1	TB11-B-M-1010-A01 Task 1	10	x	x	x	x	x	x		x	x	x	x	x			50	A.B.C	SubiD1
2	TB11-B-M-1010-A01 Task 2	12	x	x	x	x	x	x		x	x	x	x	x	x		50	A.B.C	SubiD4
3	TB11-B-M-1010-A01 Task 3	10		x	x	x	x	x		x	x	x	x	x			40	D	SubiD1
4	TB11-B-M-1010-A01 Task 4	11	x	x	x	x	x	x		x	x	x	x	x			30	C.D	SubiD2
5	TB11-B-M-1010-A01 Task 5	9				x	x	x		x	x	x	x	x	x		20	K	SubiD3
6	TB11-B-M-1010-A01 Task 6	5								x	x	x	x	x			0	L	SubiD3
7	TB11-B-M-1010-A01 Task 7	4	x	x	x	x											20	P	SubiD5
8	TB11-B-M-1010-A01 Task 8	9				x	x	x		x	x	x	x	x	x		15	C.D	SubiD6
9	TB11-B-M-1010-A01 Task 9	6	x	x	x	x	x	x									20	A.B.C	SubiD7
10	TB11-B-M-1010-A01 Task 10	7						x		x	x	x	x	x	x		30	D	SubiD8
11	TB11-B-M-1010-A01 Task 11	2		x	x												0	R	SubiD9
12	TB11-B-M-1010-A01 Task 12	3				x	x	x									0	S, M	SubiD3
13	TB11-B-M-1010-A01 Task 13	1								x							0	T	SubiD9

Fig. 7. Sample template two-week look-ahead schedule from the IGA project

The Master Schedule was converted into monthly look-ahead schedules and then converted into a two-week look-ahead schedule (Figure 7), which was shared with associated superintendents a day before coordination and review meetings. Superintendent feedback was reflected in these look-ahead schedules. The schedules were prepared using spreadsheet software, as this was the standard programme for the subcontractors. The communication and collaboration involved in this process helped to resolve key scheduling challenges at the execution level.

BU6: Field BIM for site inspection and waste reduction

An important area of BIM implementation was Field BIM. Accurate design supported fast, high-quality, onsite checks while maintaining continuous updates with the design and construction teams for zero-defect and accurate installation (Figure 8).

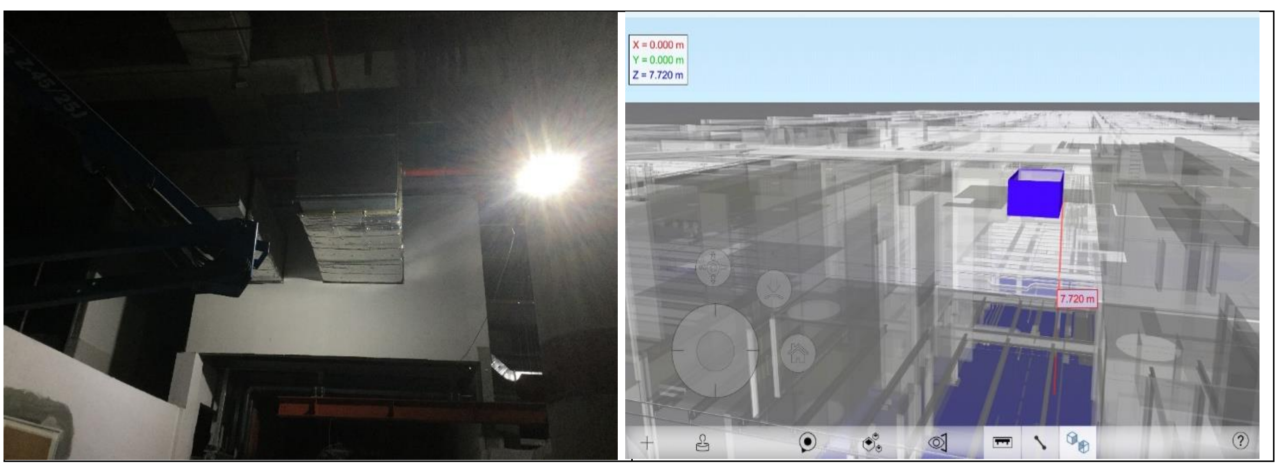

Fig. 8. Inspecting site work in the IGA terminal building

On average, 8450 notices for inspection NFIs were identified in a year through onsite mobile BIM implementation, which helped to realise a tremendous timesaving. According to the project estimates, this saving amounted to approximately 6420 person-hours or 802 person-days for the project.

BU7: Cost estimation (5D BIM for resource management)

Another important BIM use in the project was the cost estimation, often referred to as 5D BIM. This helped with the generation of reliable bills of quantities (BoQs), which supported cost measurements and estimation at both the design and construction phases. The BoQs from the BIM model were produced automatically for the technical offices.

BU8: BIM-based site health and safety management and logistics

Site management included the coordination and movement of onsite materials, people and equipment for an efficient and safe work environment. This also involved management of the onsite environmental and health and safety aspects. As illustrated in Figure 9, the site was regularly monitored and documented by the site management team, who communicated to the workforce onsite and other relevant stakeholders, which informed the coordination of logistics.

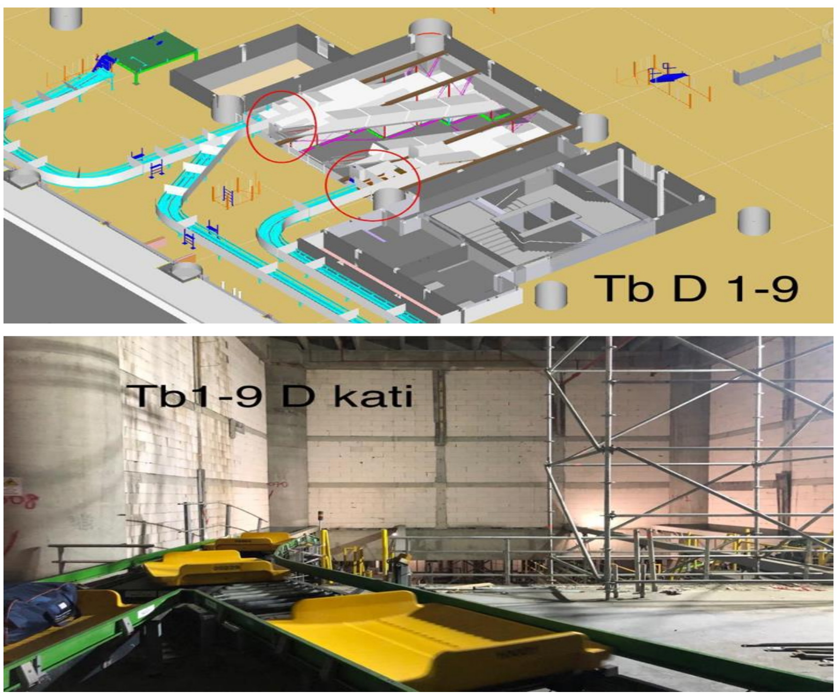

Fig. 9. Health safety analysis and onsite logistics movement in the IGA terminal

Since the construction site was highly dynamic and changing every day, it was important to specify any hazardous areas for health and safety precautions and to clearly identify and signpost the logistical transfer paths and access to the various site locations. These needed to be well-coordinated and informed to all relevant parties on site.

BU9: Managing information in a common data environment

The implementation of BIM workflows on a project of this size requires an established information management approach. A common data environment (CDE), configured according to the project's BIM execution protocols, informed the implementation of information management processes. Figure 10 is a screenshot showing part of the folder structure, layout and documents used in the project's CDE.

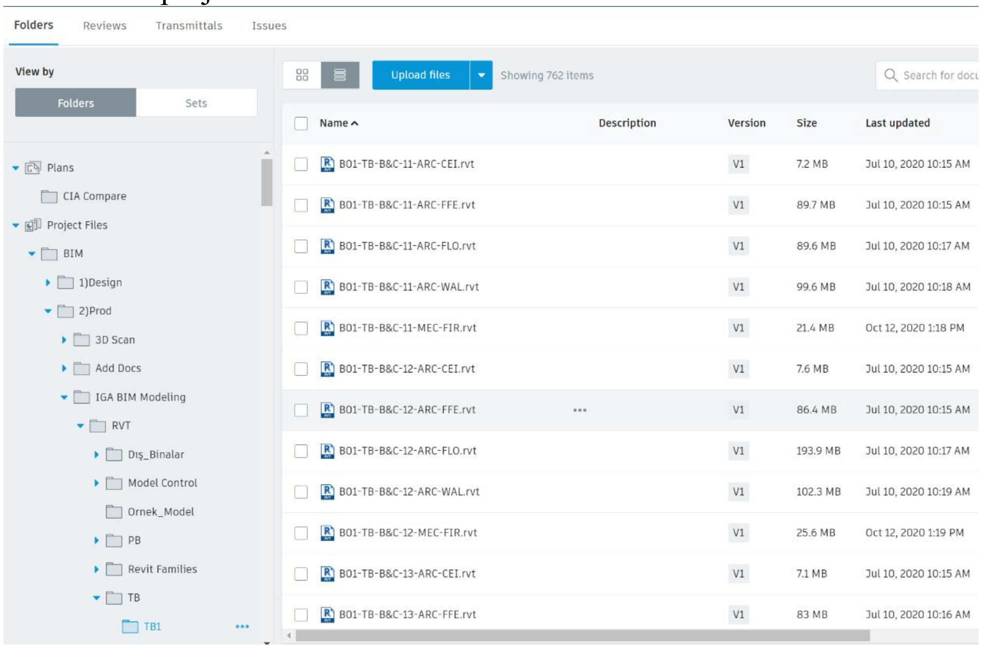

Fig. 10. CDE for document and information exchange in the IGA project

BU10: BIM-based quality assurance/checking

Another BIM application focused on quality assuring and checking (QA/QC). Using cloud-based BIM applications on tablets, this improved the speed and quality of checks, reduced unnecessary paperwork and stored the outcomes of the process in well-structured folders. One of the typical activities performed in this process was to check if site installation was being performed according to the expected requirements in the BIM model (viewable on tablets). Figure 11 shows a typical project form used in the QA/QC of heating, ventilation and air conditioning (HVAC) systems.

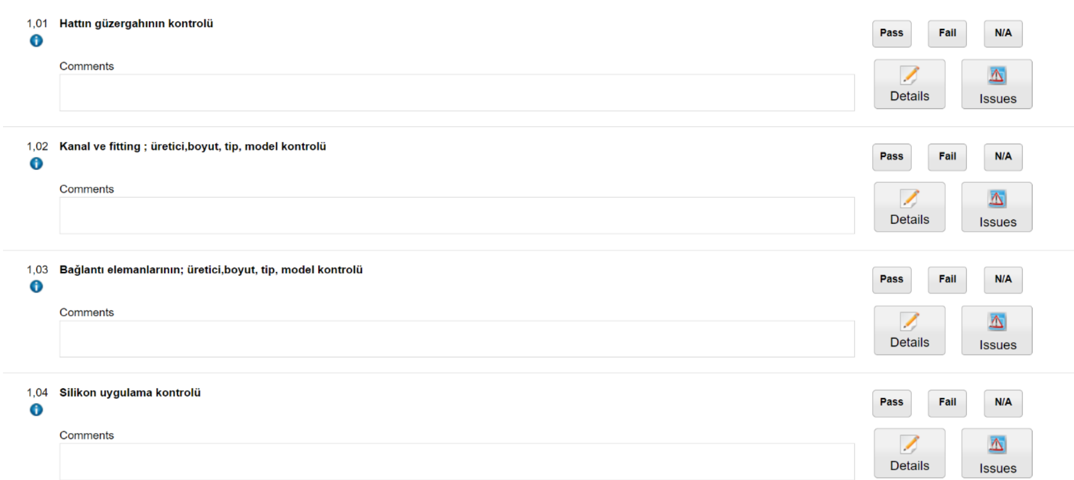

Fig. 11. QA/QC checklist for HVAC systems in the IGA project

Given the considerable size of the site, a dedicated site team was employed for the key field BIM applications, such as recording as-built information and checking for discrepancies with design information. The project parties impacting or impacted by the results of the inspection, or their potential discrepancies were given access to these records so they could implement remedies and update their information for coordination purposes.

BU11: Informing handover and operation using a BIM project model

The efficient handover of information from design to the operation/in-use phase is crucial for a project of this size, given the need for access to a progressive commissioning for its different elements. BIM was implemented to provide the information for handover in a project model database that included the operational information of key maintainable items. Figure 12 shows an example of such information for sensors and HVAC components.

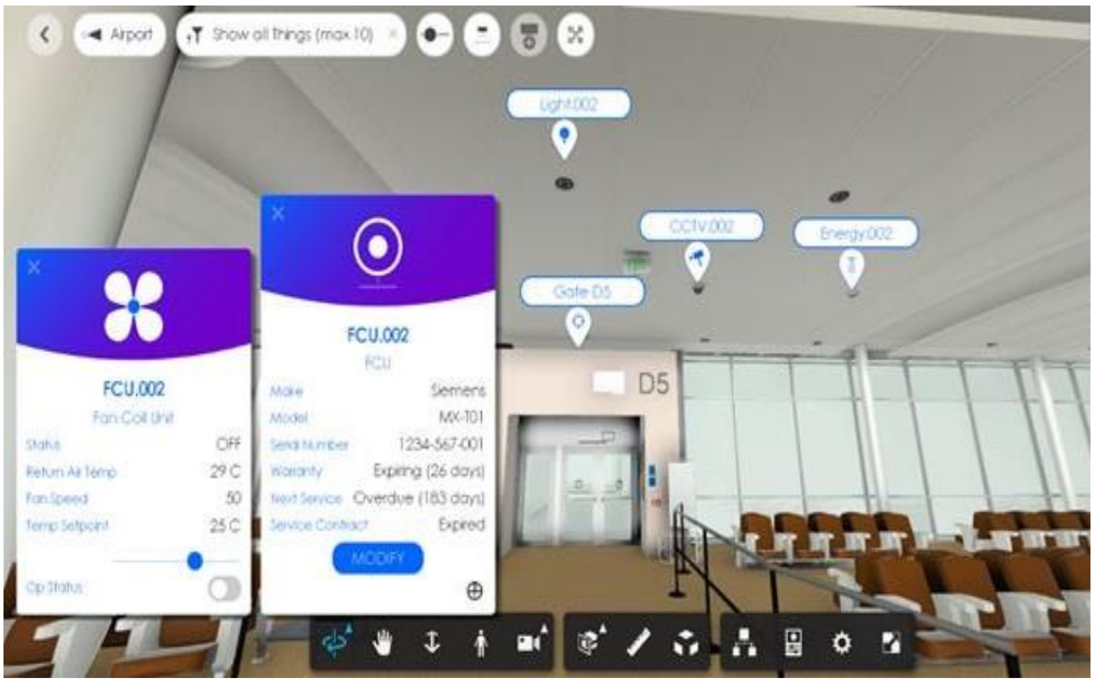

Fig. 12. Model data used for facility management from the IGA BIM model

6. DELPHI STUDY SETTING FOR THE EVIDENTIAL ANALYSIS

The correlations between BIM and LC principles were identified with the involvement of ten experts (eight practitioners and two academics) from the IGA project. Information on the selected participants in the Delphi Study is given in Tables 3 and 4.

Table 3. Criteria for Expert Selection (**D**: Desirable; **E**: Essential)

Academic participants	Industry participants
• Background in architecture, engineering and construction industry (**D**) • Knowledge of BIM and LC (**E**) • Involvement in industrial collaborations involving BIM and LC (**E**). • Teaching BIM and LC (**D**)	• Involved in the IGA case study project (**E**). • Involvement in at least one additional project implementing BIM and LC (**E**). • Experience in managing either architectural, civil, mechanical/HVAC or MEP systems (**E**) • Holding recognised certification in BIM or LC (**D**)

Table 4. Profile of Experts Selected for Delphi Study

Title	Professional Title	Experience (years)	
		Construction Industry	BIM and/or LC
EPRT-1	Civil Engineer	30-35	>15
EPRT-2	Electrical Engineer	20-25	10-15
EPRT-3	Civil Engineer	20-25	5-10
EPRT-4	Architect	20-25	5-10
EPRT-5	Mechanical Engineer	20-25	5-10
EPRT-6	Architect	20-25	5-10
EPRT-7	Architect	10-15	1-5
EPRT-8	Civil/Structural Engineer	20-25	>15
ACA-1	Professor/Civil Engineer	20-25	>15
ACA-2	Professor/Architect	30-35	>15

At Stage 4, participants were asked about the BIM and LC benefits they had observed during the IGA construction process (Figure 13), and the main initial correlations between BIM functionalities and the LC principles were determined using the responses received. The iterative steps of the Delphi method were implemented with the experts while maintaining both their anonymity and the impartiality of their responses. This encouraged the participants to reflect on their ideas without being subjected to impressions or influences from others.

The Delphi method was applied in three steps. First, the open-ended questionnaire was piloted to ensure that the meaning and purpose of the questions were clear to all participants. Then, the actual questionnaire was produced according to the response of each participant from the pilot. The items prepared were sent to the participants to rank them on a seven-point Likert scale from (1) ‘Strongly Disagree’ to (7) ‘Strongly Agree.’ After all the participants’ responses were received, the median (Md), a quarter (R), standard deviation and the frequency rate of the response between 5 and 7 were calculated, as shown in Fig 13.

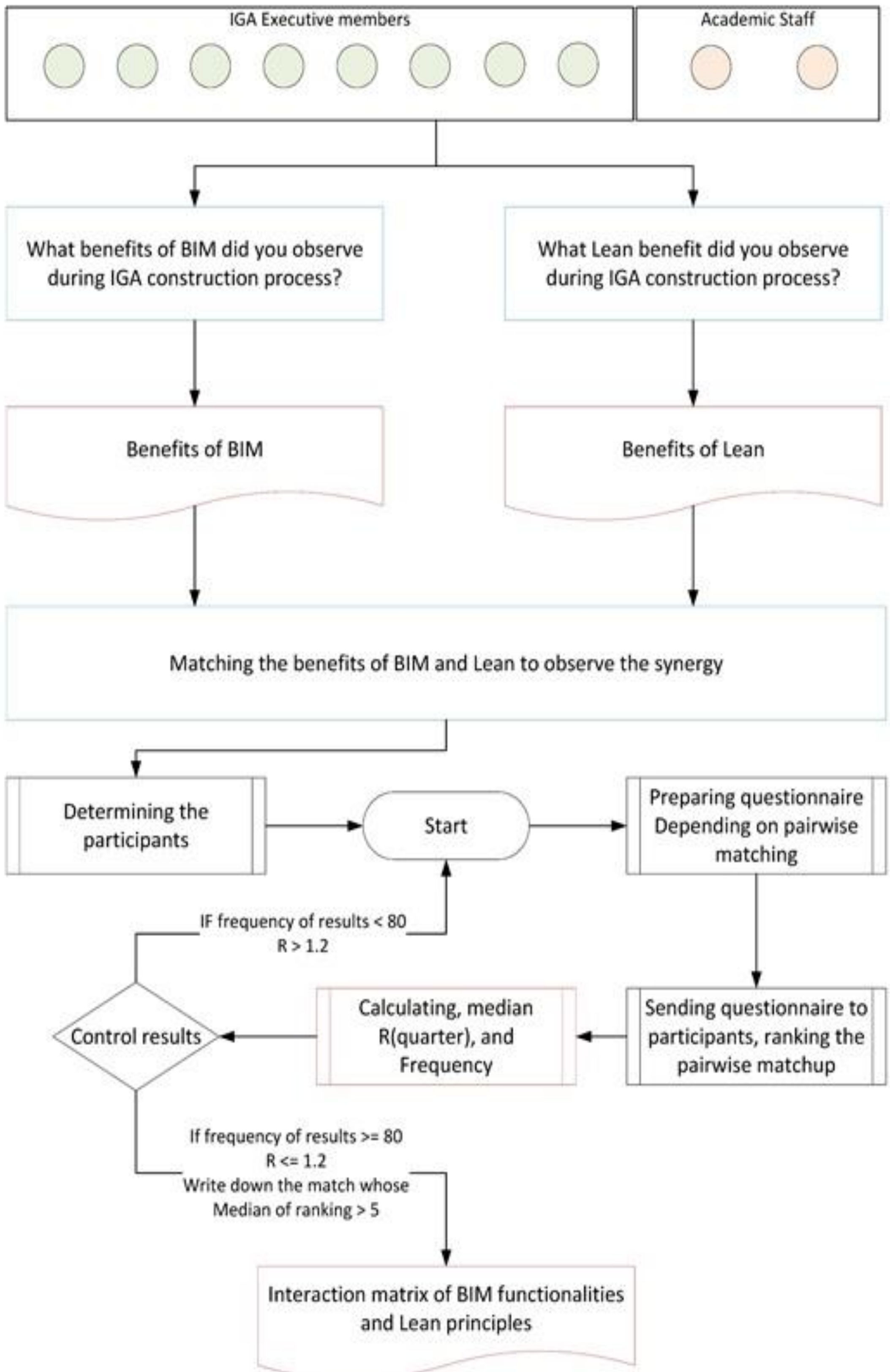

Fig. 13. Delphi process to determine correlation between BIM and LC items.

7. MEASURING CORRELATIONS BETWEEN BIM AND LC

The correlations between 11 BIM functionalities and 13 LC principles (Figure 14) were investigated by controlling the frequency of the answer and the quarter (R). If R for all matches was equal or less than 1.2 (threshold value for R) and the matches were ranked between 5 and 7 with more than 80% frequency, the Delphi process was terminated and the BIM-LC pairing correlated. Otherwise, the process restarted, with the participants repeating the evaluation round until the criteria were achieved. The additional rounds involved circulating – where applicable – an explanation of why participants felt their responses were correct.

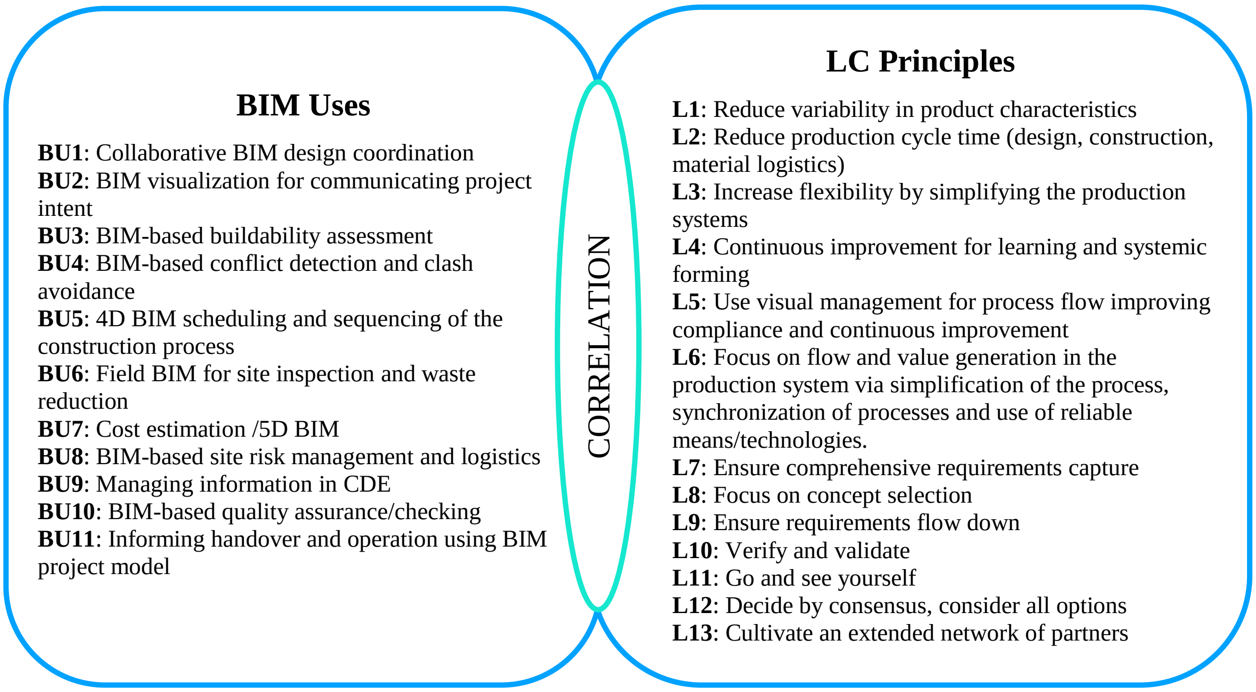

Fig. 14. Representation of BIM functionalities and LC principles

Table 4 shows the results for all the pairs in analytical terms, with the total of 46 identified correlations between BIM uses and LC principles shown in red. Correlations are shown in a matrix format.

Table 5 was extrapolated from the coloured graphs (Figure 15, 16 and 17) to evaluate the results from the Delphi study. The visual scatter plot in Figure 15 shows the results based on standard deviation and median; Figure 16 shows the level of frequency and their R values between BIM uses and LC principles; and Figure 17 shows the results for the correlation between BIM uses and LC principles observed and experienced in the project.

Two rounds were performed to gain a consensus among the panellists. In the first round, some of the pairs received low Md values with higher R values, which can be interpreted as disagreement. Therefore, more than one round was carried out to satisfy agreement. For example, for the relationships between BU1 and L1, the Md value was lower than 5 and the R value 2 in the first round. In the second round, the panellists revised their views towards accepting the proposed relationships.

Table 5. Results of the Delphi Method

		BU1	BU2	BU3	BU4	BU5	BU6	BU7	BU8	BU9	BU10	BU11
L1	**σ**	0.8717798	0.7	0	0.8	1.2845233	0.3	0.3	0.4	0.5385165	0	0.3
	Md	5.5	6	3	6	5	7	7	5	5	5	4
	R	1.75	0.75	0	1	0	0	0	0	0	0	0
	fr	0%	100%	100%	100%	100%	100%	0%	90%	100%	60%	0%
L2	**σ**	0.6403124	0.3	0.3	0.9	0.6708204	0.3	0.3	0.6403124	0.3	0.6708204	0
	Md	3	6	7	7	7	6	4	6	5	5	3
	R	1	0	0	1.75	1	0	0	0	0	1	0
	fr	0%	100%	100%	100%	100%	100%	0%	90%	100%	60%	0%
L3	**σ**	0	0.3	0	0	0.5	0	0.3	0.6708204	0	0	0.4898979
	Md	3	2	3	3	6	3	6	5	6	3	3
	R	0	0	0	0	1	0	0	1	0	0	1
	fr	0%	0%	0%	0%	100%	0%	100%	60%	100%	0%	0%
L4	**σ**	0.6	0.9219544	0.7483315	0.5	0.3	0.4582576	0	0.9165151	0.9165151	0.4582576	0.4582576
	Md	6	5	5	4	4	3	3	5	4	3	3
	R	0.75	1	1	1	0	0.75	0	1.5	1	0.75	0.75
	fr	100%	60%	60%	50%	10%	0%	0%	70%	50%	0%	0%
L5	**σ**	0.8717798	0.781025	0	0.9	0.6403124	0.7483315	0.4582576	0.6	0.4582576	0	0.4898979
	Md	4	4	6	4	7	4	4	4	4	3	5
	R	0.75	0.75	0	1	0	1	0.75	0.75	0.75	0	1
	fr	30%	10%	100%	40%	100%	20%	30%	10%	30%	0%	60%
L6	**σ**	0.7483315	0.7483315	0.5385165	0.4898979	0.5385165	0.6403124	0.4	0.3	0.4	0.6708204	0.4
	Md	5	3	5	4	6	3	5	3	7	4	7
	R	0	0	0	1	0	0	0	0	0	1	0
	fr	90%	0%	80%	40%	100%	0%	100%	0%	100%	40%	100%
L7	**σ**	0.4472136	0.8717798	0	0	0.781025	0.4582576	0	0	0.8062258	1.2489996	0
	Md	3	4	6	6	4	5	6	3	4	5	6
	R	0	1.75	0	0	1	0.75	0	0	1	2.5	0
	fr	0%	50%	100%	100%	50%	70%	100%	0%	50%	60%	100%
L8	**σ**	0.6324555	0.6708204	0.9433981	0	0.8944272	0.5	0.5	0	0	0	0
	Md	6	7	5	3	5	2	3	3	3	3	5
	R	0	1	2	0	2	1	1	0	0	0	0
	fr	100%	100%	60%	0%	60%	0%	0%	0%	0%	0%	100%
L9	**σ**	0.8944272	1.1135529	0.781025	0.4472136	0.663325	0.4	0.9433981	0.8306624	0.8062258	0.4	0.6708204
	Md	5	5	4	6	3	6	5	3	3	2	2
	R	2	1.75	1	0	1	0	1	1.75	1	0	1
	fr	60%	70%	50%	100%	10%	100%	60%	0%	10%	0%	0%
L10	**σ**	0.6324555	0.4898979	0.4	0.8	0.663325	0.4582576	0.4	1.1357817	0.8306624	0.4898979	0.7
	Md	3	2	3	2	3	3	6	2	2	3	3
	R	0	1	0	1	1	0.75	0	2	1.75	1	0.75
	fr	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%
L11	**σ**	0.4582576	0.663325	0.5385165	0.3	0.4898979	0	0.4582576	0.3	0.4	0	0.4
	Md	5	4	6	2	5	3	5	3	3	2	5
	R	0.75	1	0	0	1	0	0.75	0	0	0	0
	fr	70%	50%	100%	0%	60%	0%	70%	0%	0%	0%	100%
L12	**σ**	0.4	0.663325	0.8717798	0.6403124	0.6403124	0.3	0.4582576	0.6708204	0.4582576	0	0
	Md	5	5	4	5	7	3	5	5	5	2	2
	R	0	0.75	1.75	1	0	0	0.75	1	0.75	0	0
	fr	100%	100%	50%	90%	100%	0%	70%	60%	100%	0%	0%
L13	**σ**	0.6324555	0.8306624	0.4898979	0.3	0.6403124	0.4	0.4472136	0.4898979	0.4	0.9	0.6324555
	Md	5	5	5	6	5	6	6	5	7	5	5
	R	0	1.75	1	0	1	0	0	1	0	0	0
	fr	80%	60%	60%	100%	60%	100%	100%	60%	100%	90%	80%

In Figure 15, larger size represents the Md value. The colour coding shows the standard deviation, which was mainly lower than 1, so green is the dominant colour, implying low deviation and higher consensus among the participants in the Delphi study on the measured correlations between the LC principles and the BIM used in the project. Md value is represented as a square shape, with bigger size of the correlations indicating higher levels of collective agreement.

In other words, higher Md means higher correlation between the corresponding BIM use and LC principles, while the lower standard deviation implies higher reliability and accuracy of the correlation. Apart from the BU4-L2 correlation, all the measured correlations showed high accuracy.

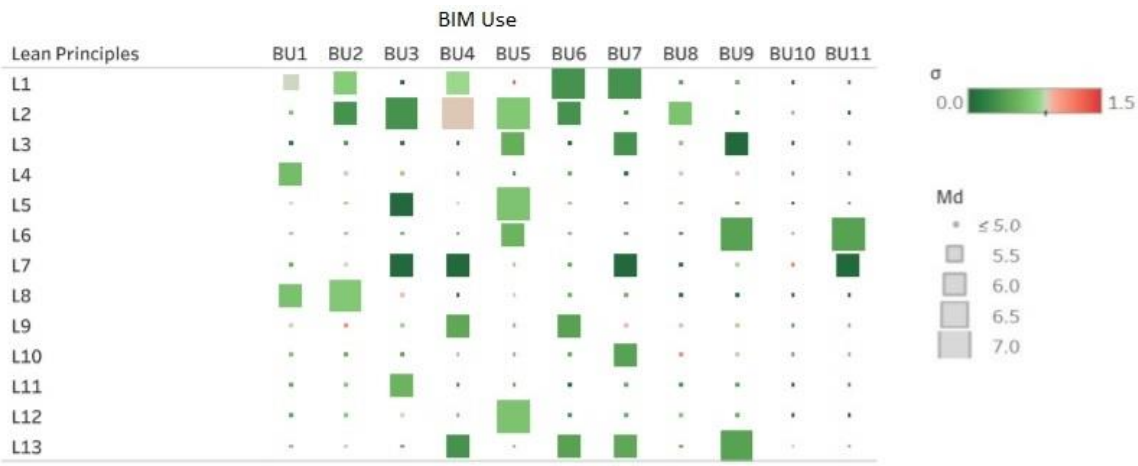

Fig. 15. Standard deviation and Md values for correlation occurrence.

The frequency of occurrence of these correlations is presented as a range (0-1). High-frequency correlations are shown in darker blue, and the low-frequency correlations in lighter blue (Figure 16). Lower range is shown by a bigger square and higher range by a smaller one.

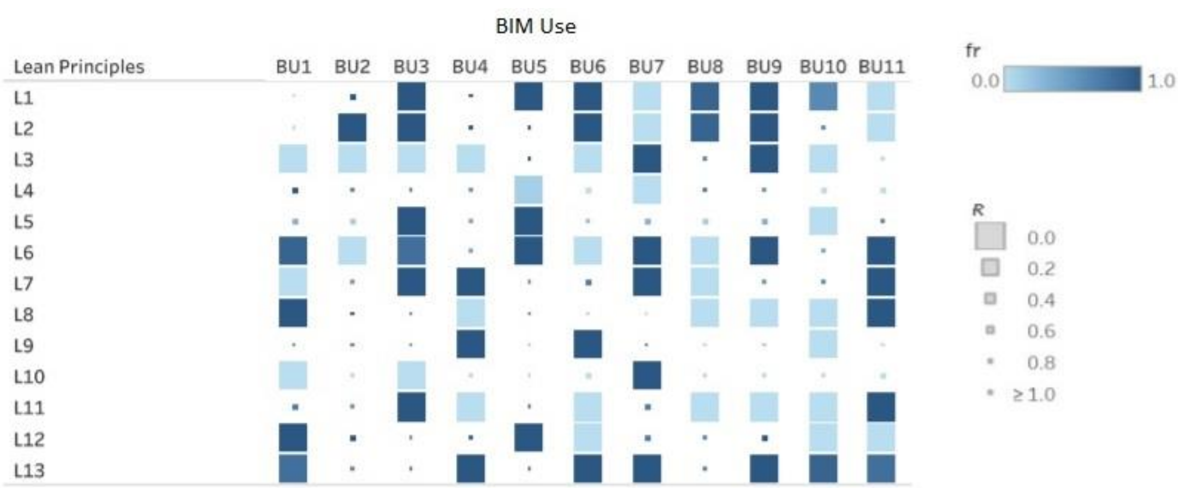

Fig. 16. Frequency and range values represented by colour and size.

Based on the findings in the above visual analysis, acceptable correlations are further highlighted graphically in the results diagram below (Figure 17). Blue boxes show correlation, while red implies no correlation.

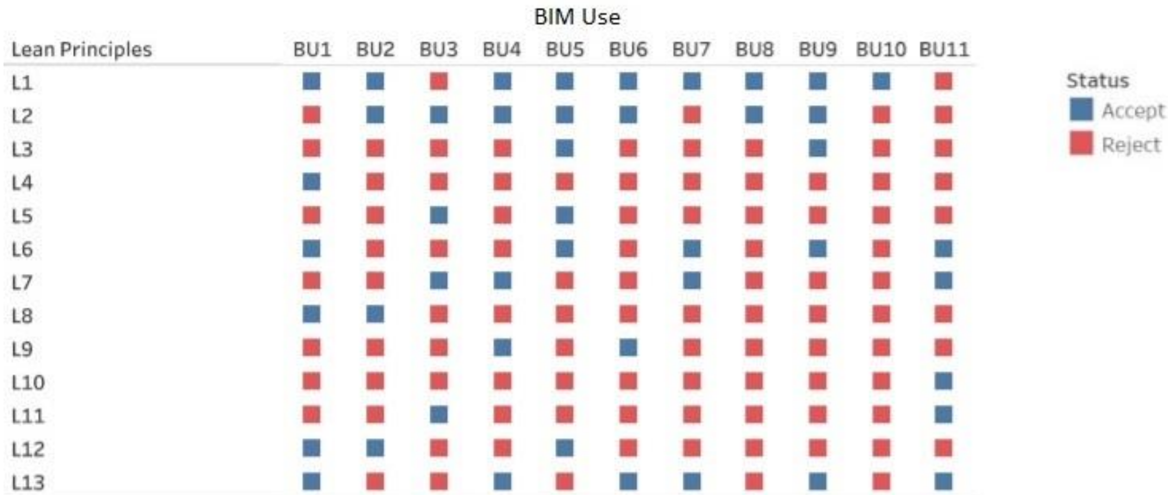

Fig. 17. Results of the Delphi method as a binary of correlation vs. no correlation.

The correlations between LC and BIM functionalities in Figure 17 are tabulated in Table 6. The correlation between the LC principles and BIM uses are found to be intensified with some LC principles (especially L1, L2, L6, L7 and L13), while other LC principles, such as L4 and L10, show weak correlations with the BIM uses.

The results indicate that certain BIM uses (BU5 to BU10) contributed to reduce variability in the IGA project while BU2, BU3, BU5, BU6, BU8 and BU9 helped to reduce the cycle times. The Delphi analysis also showed that L4 (Learning and systemic forming for continuous improvement) is clearly supported by the implementation of BU1 (Collaborative BIM design coordination). Furthermore, L8 (Focus on concept selection) and L12 (Decide by consensus, consider all options) were enabled with BU2 (BIM visualisation for communicating project intent).

Ensuring comprehensive requirements capture (L7) was supported by BU3, BU4, BU7 and BU11. Additionally, the findings show the communication of requirements to relevant downstream project parties (i.e., L9 [Ensure requirement flow down]) is supported by BU4 (BIM-based conflict detection and clash avoidance) and BU6 (Field BIM for site inspection and waste reduction). While L10 (Verify and validate) and BF11 (Site management database from the project model) have a high correlation, L10 has a weak relationship with the other BIM uses. L11 (Go and see yourself) is supported by BF3 (Enhancing Buildability) and BU11 (Informing handover and operation using a BIM project model). Finally, a high relationship was found between L13 (Cultivate an extended network of partners) and BF1, BF4, BF6, BF7, BF9 and BF11, which indicates the collaborative nature of the implementation of these BIM uses.

Table 6. LC-BIM Correlations

LC Principles	BIM Functionalities
L1: Reduce variability in product characteristics.	BU1: Collaborative BIM design coordination BU2: BIM visualisation for communicating project intent BU4: BIM-based conflict detection and clash avoidance BU5: 4D BIM scheduling and sequencing of the construction process BU6: Field BIM for site inspection and waste reduction BU7: Cost estimation (5D BIM) BU8: BIM-based site risk management and logistics BU9: Managing information in CDE BU10: BIM-based quality assurance/checking
L2: Reduce production cycle time (design, construction, material logistics).	BU2: BIM visualisation for communicating project intent BU3: BIM-based buildability assessment BU4: BIM-based conflict detection and clash avoidance BU5: 4D BIM scheduling and sequencing of the construction process BU6: Field BIM for site inspection and waste reduction BU8: BIM-based site risk management and logistics BU9: Managing information in CDE
L3: Increase flexibility by simplifying the production systems.	BU5: 4D BIM scheduling and sequencing of the construction process BU9: Managing information in CDE
L4: Learning and systemic formation for continuous improvement.	BU1: Collaborative BIM design coordination
L5: Use visual management for process flow improving compliance and continuous improvement.	BU3: BIM-based buildability assessment BU5: 4D BIM scheduling and sequencing of the construction process
L6: Focus on flow and value generation in the production system via simplification of the process, synchronisation of processes and use of reliable means/technologies.	BU1: Collaborative BIM design coordination BU5: 4D BIM scheduling and sequencing of the construction process BU6: Field BIM for site inspection and waste reduction BU7: Cost estimation (5D BIM) BU9: Managing information in CDE BU11: Informing handover and operation using a BIM project model
L7: Ensure comprehensive requirements capture	BU3: BIM-based buildability assessment BU4: BIM-based conflict detection and clash avoidance BU7: Cost estimation (5D BIM) BU11: Informing handover and operation using a BIM project model
L8: Focus on concept selection	BU1: Collaborative BIM design coordination BU2: BIM visualisation for communicating project intent
L9: Ensure requirement flow down	BU4: BIM-based conflict detection and clash avoidance BU6: Field BIM for site inspection and waste reduction
L10: Verify and validate	BF11: Site management database from the project model
L11: Go and see yourself	BF3: Enhancing Buildability BU11: Informing handover and operation using a BIM project model
L12: Decide by consensus, consider all options	BU1: Collaborative BIM design coordination BU2: BIM visualisation for communicating project intent BU5: 4D BIM scheduling and sequencing of the construction process
L13: Cultivate an extended	BU1: Collaborative BIM design coordination

network of partners	BU4: BIM-based conflict detection and clash avoidance BU6: Field BIM for site inspection and waste reduction BU7: Cost estimation (5D BIM) BU9: Managing information in CDE BU10: BIM-based QA/QC

L1 (Reduce variability in product characteristics) and L2 (Reduce production cycle time [design, construction, material logistics]) were involved in the highest number of correlations (nine and seven, respectively). This result shows that in the IGA project, the team focussed their effort on fulfilling these principles through a variety of BIM uses. On the other hand, there was only one correlation between L10 (Verify and validate) and the BIM uses – with BF11 (Site management database from the project model) – which indicates that more attention was given to this task at the site stage.

The BIM uses that were involved with the highest number of correlations (i.e., six) with the LC principles were BU1 (Collaborative BIM design coordination) and BU5 (4D BIM scheduling and sequencing of the construction process). These are followed by BU4 (BIM-based conflict detection and clash avoidance), which is involved in five LC relationships.

These empirical findings on LC-BIM correlations identified analytically through the application of the Delphi method are supported below with factual information from the IGA project.

8. DISCUSSION

The Delphi method identified the correlations between LC principles with BIM uses based on the input and opinion of experts. Stage 3 (covered in Section 5 above) detailed the BIM uses involved in the IGA project. This section uses information from the IGA project to further support the findings by rationalising the LC gains achieved.

LC gains via collaborative BIM design coordination (BU1) and cost estimation (5D BIM) (BU7)

The clash-free BIM model with input from all relevant disciplines supported the necessary engineering decisions and reduced the potential negative effect of defective design on downstream work. Indeed, information from the design model was shared with the site staff using the mobile BIM applications, which also contributed to reduce *lead and wating times* onsite and informed site operation. *Flexibility* was also enabled via the collaborative BIM design model in terms of adapting the design solution to new, different, or changing requirements.

LC gains via BIM-based conflict detection and clash avoidance (BU4) and managing information in CDE (BU9).

All collaborations and data exchanges were initially made through paper-based project documentation. Engineers visited the technical office to discuss project details on the (hard copy) project drawings. This process was not practical for managing the project execution on site due to the high complexity and ambiguities of a mega project (the area of the construction work in this project amount to 76.5 million m^2). Concurrent engineering and synchronised collaboration between the site staff, subcontractors and consultant firm staff was desperately needed.

With the increasing implementation of the key BIM uses, such as BU4 and BU9, the benefits of *flexibility*, concurrent engineering and *effective collaboration* started to emerge. The information management via the CDE and the supporting protocols (BU9) facilitated project parties' access to information. BU9 contributed to *resolve the design and construction conflicts*, and relevant information was communicated to the field via mobile BIM technologies, ensuring that any design change or installation information was delivered to the site instantly and *resulting in fewer onsite issues (e.g., less rework and delays).*

The site engineers were able to follow the latest design information with periodic updates, *eliminating the lead time* of the physical travel distance between the office and the site. The site engineers were also notified immediately after each upload to the project library, and they were able to check for the latest revisions of their project information. This helped to *reduce the duplication of information* and the use of outdated versions of shop drawings. Figure 18 shows an example of the collaborative design checking process and the use of this information on site. This illustrates the benefits of coordinating design, the timely access to the latest design information and its onsite use to *reduce delays (e.g. waiting for instructions)* and *avoid rework (e.g. mistakes from using inaccurate or outdated design information).*

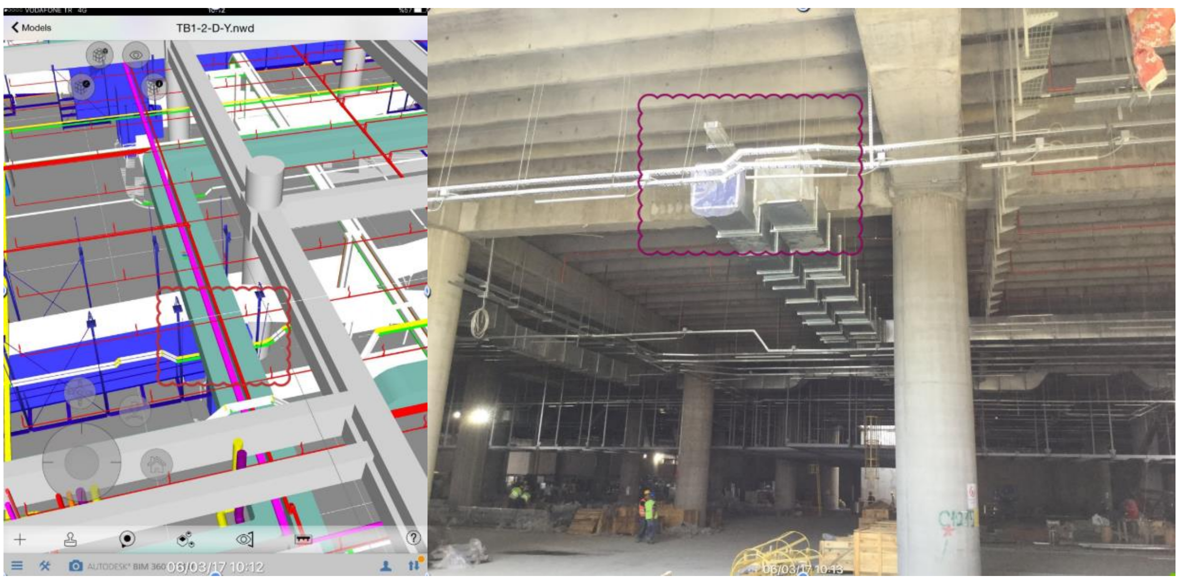

Fig. 18. Clash detection/avoidance and onsite activities in the IGA terminal building construction

The resolved design and construction clashes had a significant impact on the project. It was estimated that approximately *16.4 million man-days and €835 million savings* were achieved in the project via the rectification of 601,918 design clashes before they materialised on site, which represented approximately 10% of the total budget for Phase 1 of the project. This calculation was executed by the project team six months before the completion of Phase 1 and is considered conservative as it does not account for the benefits that may have occurred in the last six months of Phase 1 (i.e., during its completion).

LC gains via 4D BIM scheduling and sequencing of the construction process (BU5)

Look-ahead scheduling was utilised to control the production as a planning tool. However, integrating look-ahead scheduling with 4D BIM planning brought *new capabilities* that enabled the team to *finish the project on time*. The use of the clash-free model in the 4D tool *improved the communication and confidence in the scheduling function* and its role *in informing production schedules*. Utilising the 4D model during look-ahead meetings helped the project team to *identify unforeseen problems* and *resolve them at the planning stage*, which would not be easily identifiable when using spreadsheets only.

LC gains via BIM visualisation for communicating project intent (BU2) and BIM-based QA/QC (BU10).

Visualisation and cloud-based BIM applications onsite *improved site operations and control*. BIM provided an accurate information model of the design intent, which enabled the coordination of the material resources required for each work segment. Visualisation was also used in project control in a dashboard form, which *improved planning and scheduling* by informing the just-in-time arrival of people, equipment, and materials. Figure 19 shows an example of the visual dashboard used to coordinate quality inspection and assurance on site.

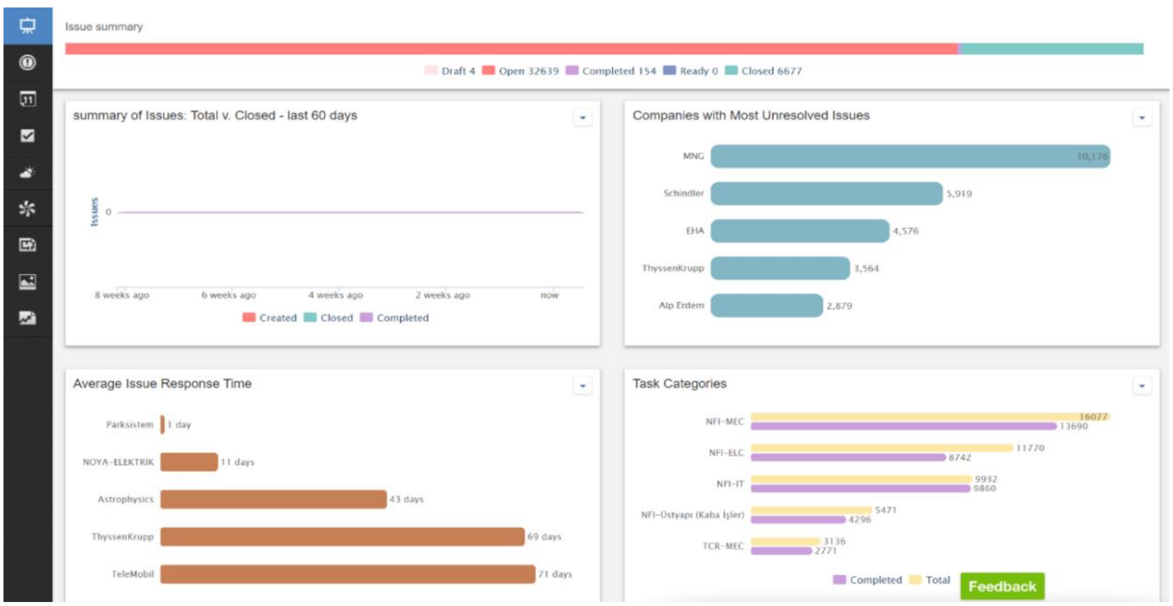

Fig. 19. Issue and task management dashboard in the IGA project

LC gains via BIM-based buildability assessment (BU3), field BIM for site inspection (BU6) and BIM-based site risk management and logistics (BU8)

Dedicated model-based review meetings were held to inspect the design and construction options for buildability purposes. This helped to *prevent issues before they reached the construction site* through shop drawings and other construction documents. Site personnel were able to access the outputs from the buildability assessment, which resulted in *fewer Requests For Information (RFIs) and enhanced personal productivity*, *effective prefabrication processes and communication between the project teams*.

Reliable information used by the construction sites, coupled with fewer RFIs and changes order, also contributed to *improving safety, logistics, and productivity*. This enabled the team to *accelerate the schedules and reduce the time-dependent project costs*. Since this was a mega-scale project, it required some fast-tracking and the planning of synchronised batch sizes to control completion time.

In this case study, the use of synchronised and larger batch sizes helped to *reduce duration compared* to the approach with synchronised and smaller batch sizes. It is known that when synchronisation and fast-tracking are used in projects, rework and other types of risks increase. However, in this case study, the support provided by BIM uses, such as BU2, BU3, BU6 and BU8, helped the implementation of the planning approach without increased risk.

LC gains via informing handover and operation using a BIM project model (BU11)

The BIM-based handover of *reliable information* occurred not only between the design phase and the construction phase but was also extended to include the handover and operation phases. The IGA BIM model, including the 3D and semantic data for the design and engineering systems of the airport facilities, was used to facilitate these transitions. The construction BIM model included the site management's necessary information that helped the *effective execution of site works*.

The look-ahead 4D BIM model was used to plan and coordinate the site works. Superintendents were given the opportunity to observe production before the coordination meetings in the form of look-ahead schedules. During the meetings, the superintendents were encouraged to comment on their progress and share their views about their tasks and the look-ahead schedule. All progress data were collated and inputted into the scheduling program. This process, supported by BIM models and visualisation, helped to *facilitate coordination* of this complex project with hundreds of subcontractors involved. The subcontractors could also share lessons about key challenges and issues they faced. Another important benefit of BU11 was in *informing the progressive commissioning* of airport facilities by providing key information for maintainable items.

9. SIGNIFICANCE

This research provided an analytical diagnostic approach for the level of interaction and correlation between LC and BIM uses in construction management on a mega scale airport construction project. Although in the literature, it is addressed that they are complementary to each other for better implementation of each, this paper diagnoses which LC principles can be achieved via which BIM uses as tabulated in Table 6 that is produced from the analytical study with Delphi.

Efficiency and effectiveness in construction are significant paradigms and these are the ultimate targets to achieve in construction under the sustainable design and construction umbrella. This is truly possible via process improvement, not just technological advancement, which only help for workflow improvement. Thus, LC practice is critical for process improvement and the level of maturity for LC is key here to ensure such efficiency and effectiveness in projects. At that point, informed decisions on BIM Uses are significant for the high maturity practice of LC. This will also in turn make the BIM implementation at high maturity from the process, tools, and data management perspectives. Hence, this paper provides a granulated findings based on the evidential analysis to diagnose the correlation between LC and BIM Uses so that treatments in the projects for efficiency and effectiveness can be better informed about which BIM Uses are needed and essential for the targeted LC gains.

10. CONCLUSIONS

The aim in this paper has been to identify and measure correlations between BIM and LC using an evidence-based approach supported by both quantitative as well as qualitative evidence. A major building project, the construction of the Istanbul Grant Airport, was used as a case study to support the investigation. The Delphi method was employed to analyse and measure the correlations between 11 selected uses of BIM and 13 LC principles. The correlations were analysed with use cases covering the design and construction phases. The Delphi analysis helped to identify and measure an array of correlations between the uses of BIM and the LC principles, providing evidence of their complementary roles in improving efficiency and effectiveness in construction projects. The qualitative analysis of data from the IGA project showed practical examples and evidence of the benefits resulting from the implementation of BIM and LC. The granularity of analysis (i.e., with 11 BIM uses and 13 LC principles) and the approach used (combining quantitative and qualitative methods) to provide evidence about the correlations constitute an important contribution to theory.

Indeed, the findings of previous studies, such as Gerber et al. (2010) and Zhang et al. (2018), who explore the notions of complementarity between BIM and LC, were extended by this study with the identification and measurement of 46 key correlations between BIM and LC principles. This study revealed the correlations between LC principles and BIM uses to be intensified with five of the 13 principles (L1, L2, L6, L7 and L13). Although two LC principles – L4 (Learning and systemic forming for continuous improvement) and L10 (Verify and validate) – showed weak correlations with the BIM uses, it was found that they could be separately supported with BU1 and BU11, respectively. Moreover, the findings indicated that BIM uses helped to both reduce variability and reduce cycle times in the IGA project.

The correlations analysed were further considered and explained with their implementations in the IGA project. Thus, it is believed that the LC principles are evidentially tested and proven.

This study contributes to the existing knowledge by its investigation and explanation of the degree of correlations between BIM uses and LC principles through a granular and evidence-based analysis in a real-world project. Therefore, the results also have practical implications. They can inform large-scale projects, such as airport terminals, hospitals, schools and universities, and commercial construction projects, regarding the importance of using both BIM and LC, and they can guide project directors and managers in the selection of specific uses of BIM to combine with LC practices.

Research limitation can be considered that this study was implemented on a single mega project since the available research capacity was only enough to focus on one mega project. When multi-case study was studied, evidence-based analysis would have higher reliability and construct validity. This would also be recommended to extent the research on other mega projects for theorising the correlations based on quantitative evidence, which can lead to theories for strategic decision making in design and construction for effective BIM use with LC principles.

Acknowledgment

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