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Building Information Modelling, Integrated Project Delivery, and Lean Construction Maturity Attributes: A Delphi Study

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Abstract: The benefits of adopting collaborative approaches in the construction industry, such as Building Information Modelling (BIM), Integrated Project Delivery (IPD), and Lean Construction (LC), in an integrated manner are widely acknowledged in academia and industry. Once organizations have embraced BIM, IPD, and LC integration (BIL), a measurement method for evaluating their progress and planning for continuous improvement is required. However, there is no widely accepted capability assessment model, such as Maturity Models (MMs), to effectively assess productivity improvements in organizations adopting all three approaches based on the interdependencies between them. The first step in the process of BIL MM development is identifying the critical attributes of BIM, IPD, and LC integration. This research investigates the interrelationships of BIM, IPD, and LC for use in the maturity models, determining how BIM and IPD can support the application of LC principles. The mixed methods approach was adopted, and a literature review and a two-round Delphi survey were conducted for the data collection. The findings revealed a number of complementarities between BIM, IPD, and LC. The panel of experts agreed upon the five major attributes and 24 sub-attributes of BIM, IPD, and LC, which formed the structure of the presented integrated BIL framework. The significance of this study is to provide the basis for organizations that intend to implement BIM, IPD, and LC in an integrated manner. Interrelating these attributes in a maturity framework also supports the planning and evaluation of organizations' progress towards realistic goals for continuous improvement.

Keywords: building information modelling; lean construction; integrated project delivery; attributes; maturity

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1. Research Background and Motivation

The construction industry has been criticized for its lack of process integration, non-cohesive teams, and inefficiency in project delivery [1]. Multidisciplinary groups in various organizations face complications and uncertainties due to the fragmented nature of traditional practices. These issues constrain efficient information sharing, resulting in a breakdown in daily communication, rework, and inefficiency in project performance and delivery [2].

According to Sacks et al. [3], the architecture, engineering, and construction (AEC) industry have addressed these issues with the adoption of collaborative approaches, including Building Information Modelling (BIM), Integrated Project Delivery (IPD), and Lean Construction (LC). BIM is a computer-generated representation of precise physical and functional data required to support the entire construction lifecycle activities [4]. Jones defines IPD as the process by which the parties are involved in a construction project from the beginning to project close-out [5]. LC is a process that aims to improve collaboration among construction stakeholders to maximize value and minimize waste [6].

Both in theory and practice, the added value of integrating BIM, IPD, and LC for collaborative processes has been acknowledged [7]. However, numerous uncertainties persist regarding implementation techniques and the actual performance of combined BIM, IPD, and LC synergy (BIL). For instance, organizations aiming to develop BIL deliverables may encounter difficulty recognizing and prioritizing their requirements. Furthermore, once organizations fully embrace BIM, IPD, and LC integration, a strategy for assessing the current status and planning realistic goals for continuous improvement will be required. Also, success claims cannot be factually justified in an organization unless a standard benchmarking mechanism for integrating BIM, IPD, and LC is available. In addition, the availability of industry discussions and academic literature claiming that BIL synergy can increase productivity has yet to be matched by the availability of widely accepted assessment tools, such as Maturity Models (MMs).

A MM can be characterized as a ladder that enables businesses to move from one level of capability to the next higher level over time, determining the current status and charting the transformation path [8]. Since the late 1970s, when the maturity model concept originated in software engineering, it has spread to various management disciplines, including project management, construction management, and others [9]. Examples of models that have been adopted in the construction industry are “Standardized Process Improvement for Construction Enterprise (SPICE)”, “Project Management Process Maturity (PM2)”, “National BIM Standard’s Interactive Capability Maturity Model”, and “Lean Construction Maturity Model (LCMM)”.

Since then, several BIM, LC, and IPD-related MMs have been developed. An analysis of the “Maturity Evaluation Scope” of existing MMs revealed that most models focused on only one approach at a time or cautiously integrated them into a second paradigm in which their aspects were partially incorporated [10]. For instance, the “Lean assessment baseline tool for Ireland” and “Lean-IPD Health Assessment Tool” are two models introduced and developed by the Lean Construction Institute to measure LC-IPD integration [11]. Despite the few BIM features in both models, neither can be considered a BIM-IPD-Lean model, as they only touch on BIM-related aspects. As a result, little attention has been paid to integrating BIM-IPC-LC in the context of MMs. In addition, there is no solid theoretical background for determining the structure of the MMs’ attributes [12].

The maturity models across these three approaches are developed using different methodologies. Likewise, the structure of each model is unique, covering a range of different attributes and sub-attributes. The literature review showed that identifying attributes based on the literature and applying the Delphi methodology to validate them are frequently used in developing MMs, such as the BIM Maturity Matrix, Owners BIM CAT, Multifunctional BIM, and Maturity Model [13]. Likewise, the present study focuses on the BIL synergy attributes based on the current literature to identify the most critical attributes. It then applies the Delphi method to validate the proposed attributes and form the BIL framework.

The scholarly studies acknowledge the significance of BIM and IPD in directly fulfilling LC principles. For instance, it is highlighted by Evans et al. that BIM is a collaborative design-sharing platform that helps achieve LC principles [14]. Likewise, IPD maximizes the value for involved parties through collaboration improvement [15]. With this in mind, this study presents the following hypothesis and the consequent research questions:

H1. *BIM and IPD can support the implementation of LC principles.*

H2. *The BIM, IPD, and LC interdependencies can serve as the basis for an integrated maturity framework structure.*

The primary research questions are:

1. What critical attributes must be assessed in evaluating BIL maturity?
2. What is the perceived importance of those attributes by knowledge-related experts?

To address these questions, this study (a) recruited a panel of qualified BIM, IPD, and LC experts to participate in a Delphi survey; (b) asked the panel about the importance of the identified set of attributes and sub-attributes in evaluating BIL competencies; (c) assisted the panel in reaching an agreement on the perceived significance of such attributes; and (d) provided the basis for the future BIL MM.

2. Research Methodology

The methodology used in this research is structured into three phases:

1. A set of attributes were established for developing an integrated MM based on Diekmann et al. and Koskela LC principles [16,17]. The two LC studies are referred to as they convey highly cited definitions of the LC principles in the literature.
2. The second phase involved compiling a list of sub-attributes to link BIM and IPD to LC principles and establishing the second level of the BIL framework based on the literature. Some attributes were also identified by reviewing the existing BIM assessment tools;
3. Two rounds of the Delphi method were used to validate the attributes through an agreement among the selected participants. The Delphi method is used when there is no explicit agreement or actual resources on a specific phenomenon, such as BIL attributes [18]. There are various techniques to initiate the Delphi survey's development phase. Some studies begin with open-ended questions designed to collect expert suggestions [19]. However, most studies begin with a literature review to establish an initial list of attributes that can be revised and evaluated by the Delphi panel [20]. Hence, using a structured questionnaire and open-ended questions in the Delphi rounds is common. This technique was applied to evaluate the significance of proposed attributes and retrieve other attributes that had been overlooked in the literature review round [21] (Figure 1).

   Each phase of the proposed method has been elaborated on in the following sec-tions.

2.1. BIL MM Attributes Identification

The first step in MM development is identifying critical attributes [22]. The backbone of the attributes' structure is the collaboration of the BIM and IPD to address the LC principles. Different academics describe the LC principles differently. Although they adhere to the same concepts or ideas, they convey them with various terminologies. Koskela brought Lean thinking to the construction industry and listed the principles as follows [23]:

- "Reduce the share of non-value-adding activities, cycle time, and variability;
- Simplify by minimizing the number of steps, parts, and linkages;
- Increase output flexibility and process transparency;
- Increase output value through systematic consideration of customer requirements;
- Focus control on the complete process;
- Build continuous improvement into the process;
- Balance flow improvement with conversion improvement and benchmark".

Each phase of the proposed method has been elaborated on in the following sections.

Diekmann et al. reviewed the Lean principles and identified five fundamental principles. The model has proven to be easily implemented and interpreted by the construction supply chain, including those with technical or non-technical languages [24]. The principles are as follows:

- "Customer focus;
- Culture/people;
- Workplace standardization;
- Waste minimization;
- Continuous improvement".

A detailed analysis of these two LC perspectives revealed a high degree of similarity and overlap in their characteristics. The resulting mutual points served as the basis for formulating the BIL maturity framework's structure, attributes, and sub-attributes. The LC principles' characteristics that did not immediately correlate were also incorporated into the proposed structure of the BIL framework due to their novelty and the unique viewpoint they provided on the LC principles. In a different round of analysis, some attributes were further customized based on the literature and the review of the existing model, with some adjustments and breakdowns to demonstrate the contribution of BIM, IPD, and LC techniques in greater detail. In some cases, sub-attributes were merged into a single attribute due to high similarity, and irrelevant ones were eliminated due to the customization of the two LC principles. The relevance of the principles from both LC perspectives is summarized and illustrated in Figures 2–6. Light grey lines connect each LC perspective's key characteristics to further detailed ones. Dashed yellow lines in the figures also represent dependency relationships between the two perspectives. Following different rounds of detailed literature review, this study identified five attributes and 26 sub-attributes, which will be further elaborated on in the next sections.

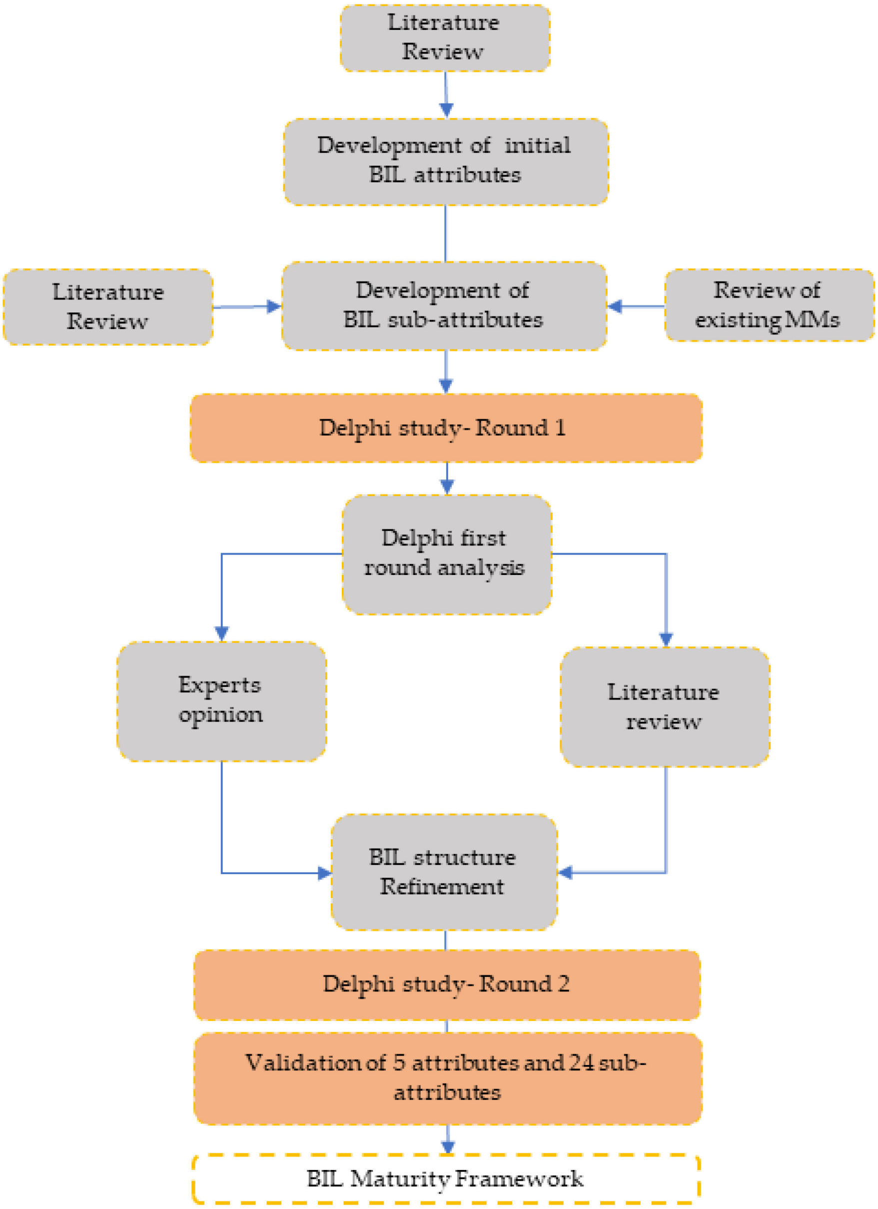

Figure 1. Research Design.

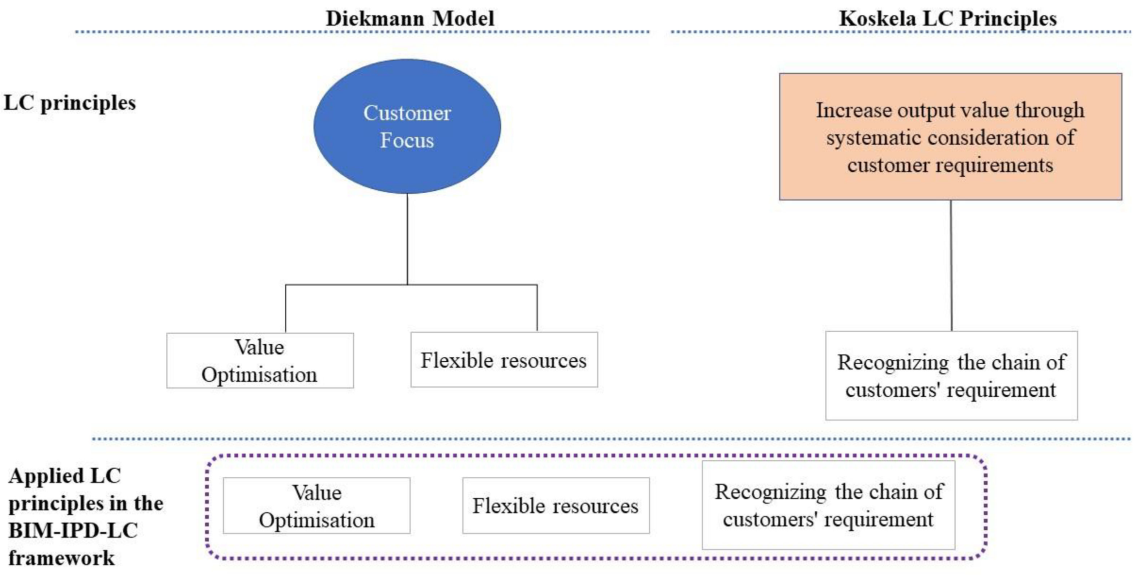

Figure 2. Diekmann and Koskela's LC principles [16,17], customer satisfaction.

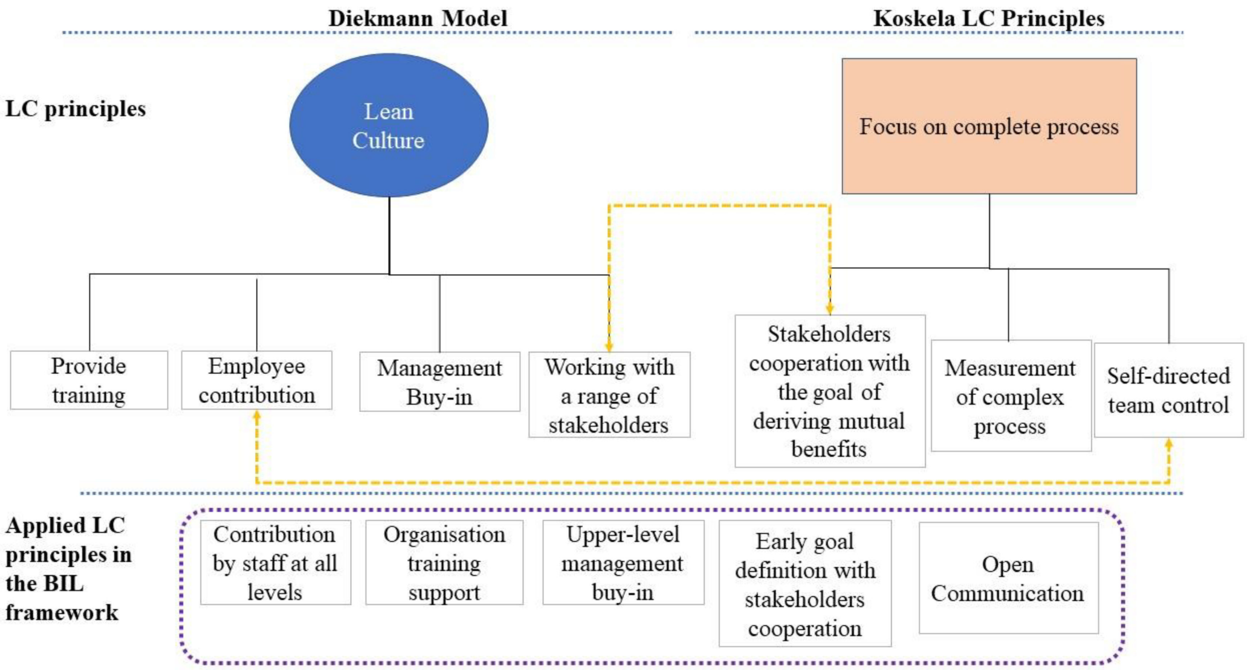

Figure 3. Diekmann and Koskela's LC principles [16,17]-culture.

2.1.1. Customer Focus

The Diekmann model's customer focus characteristic comprises two sub-attributes: "flexible resources" and "value optimization". In addition to these two, Koskela has separated the value into (1) external value: the customer value, and (2) internal value: the value amongst the delivery team. As a result, the current study added "Recognition of the entire supply chain as a client chain" to the sub-attributes layer [25] (Figure 2).

The "flexible resources" attribute deals with the ability of an organization to adapt in response to clients' requirements. Indeed, it involves the organization's ability to meet the client's needs and potential changes, which necessitates flexibility in technologies, teams, machinery, materials, and skills [26]. For instance, the availability of multi-skilled staff can enable the team to change the project's direction to meet customer needs by generating numerous alternatives in the BIM model [27].

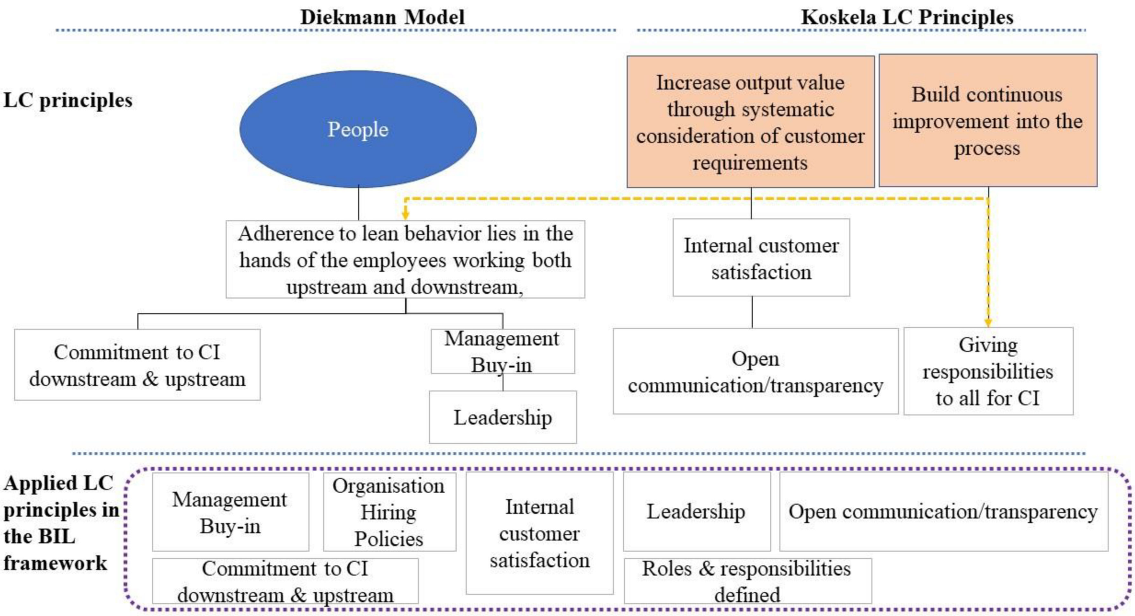

Figure 4. Diekmann and Koskela's LC principles [16,17]-people.

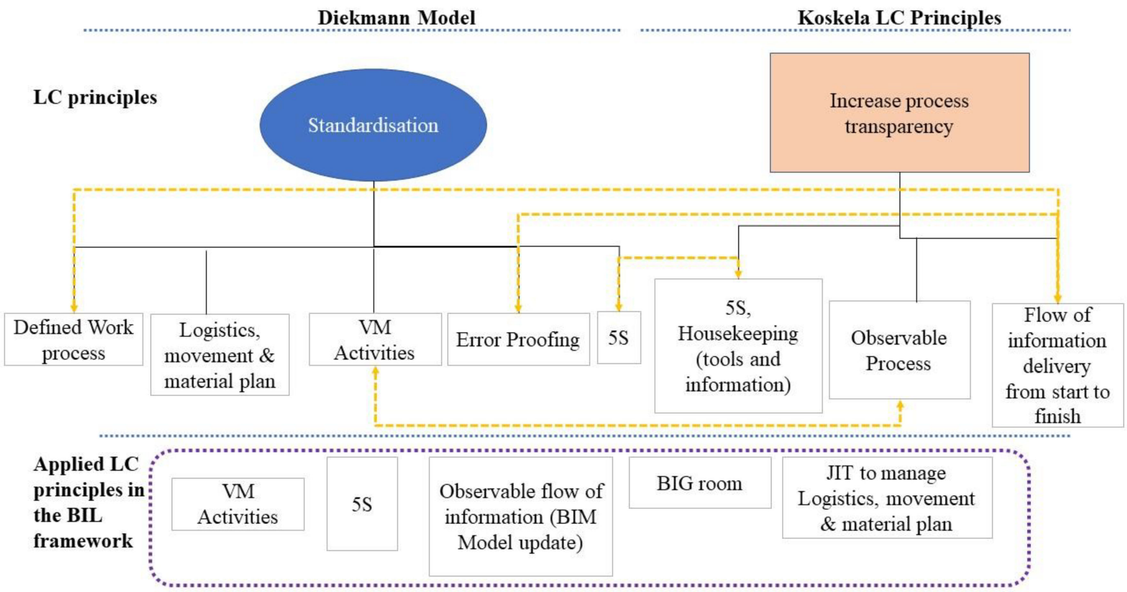

Figure 5. Diekmann and Koskela's LC principles [16,17]-standardization.

"Optimizing value" concerns maximizing the project's outcome by understanding the customer value to plan accordingly and meet these values effectively. Even though value cannot be defined universally, the IPD parties can agree on established value meanings for both soft values (e.g., better communication) and hard values (e.g., adhering to budget and time requirements and project quality) [28]. Hence, the most important part of delivering value is ensuring that all of the client's needs are taken into account and that information flows to the location where value can be added [29]. The former can be achieved using IPD contracts and early engagement of participants, while the latter can be accomplished using BIM and LC approaches. For instance, BIM can generate alternatives and solutions according to the client's value perception and test those alternatives on energy and structural analysis, cost estimation, and analysis of conformance with construction codes in order to produce high-quality projects within budget and on schedule [30].

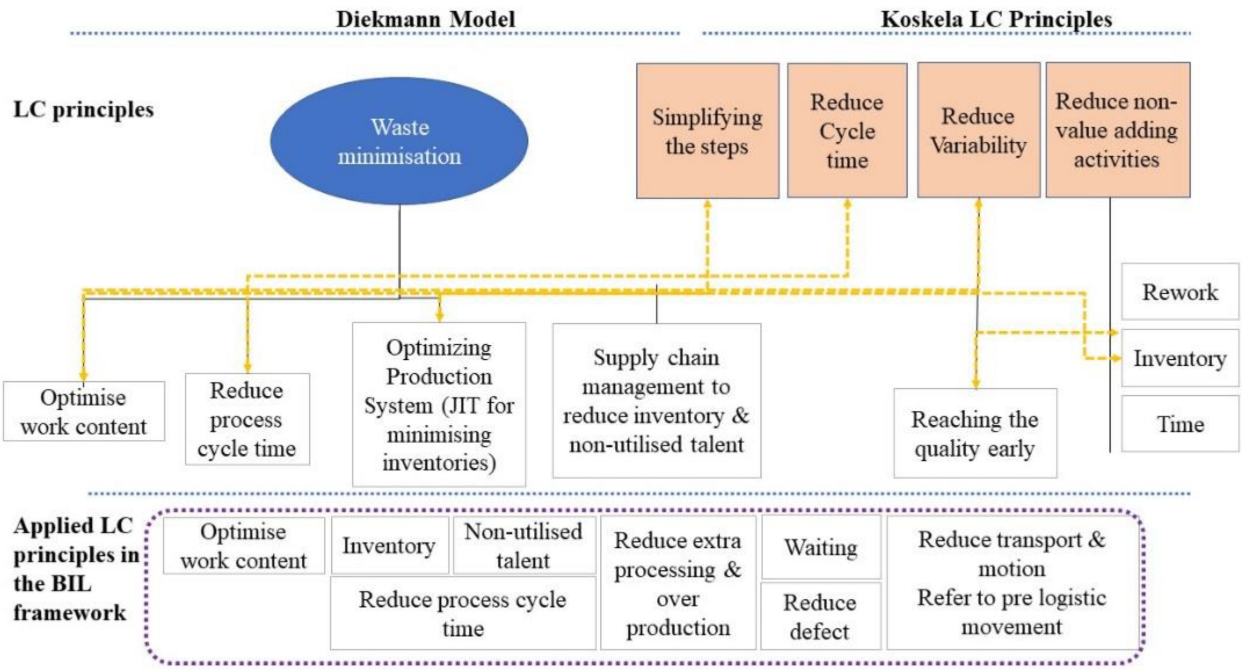

Figure 6. Diekmann and Koskela's LC principles [16,17]-waste minimization.

2.1.2. Culture/People

The transition to LC results in changes in the organization's culture and mindset to actively engage all people's points of view in the project, regardless of their position. Without the full participation of everyone involved, LC will not reach its full potential [31,32]. The "culture/people" attribute focuses on respecting people and allowing them to contribute to their maximum potential by aligning their work with customer value and the vision of the organization's strategy [17]. From both Diekmann's and Koskela's perspectives, "people" and "culture" can be divided into two distinct categories. In this research, their principles were first reviewed separately to better analyze their detailed characteristics. They were then grouped back under a single principle (people/culture) since there were numerous overlaps (Figures 3 and 4).

"Lean culture" and "focus on the complete process" cover the cultural aspects of LC. As shown by the dashed line, the sub-attributes that share mutual points are: "employee contribution" and "self-directed team control", "working with a range of stakeholders", and "stakeholder cooperation". The rest of the sub-attributes that bring different perspectives were also added to the BIL sub-attributes.

According to the "people" characteristics, both viewpoints highlight the significance of the contribution of all employees working upstream and downstream hand in hand to establish Lean behaviour and continuous improvement throughout the entire organization. This could be accomplished by combining "management buy-in", "a Lean leadership style", "open communication to create trust", and "establishing the LC culture by assigning each staff member particular Lean responsibilities".

With another round of deep study into the characteristics, similarities, and novelty of the mentioned attributes resulting from both "culture" and "people", the final set of sub-attributes were summarized as "contribution by all staff", "organization training support", "upper-level management buy-in", "early goal definition with stakeholder cooperation", and "availability of open communication" to facilitate the process and improve the cooperation inside the organization with internal staff and outside the organization with the stakeholders (Figure 4). "Internal customer satisfaction" and "commitment to continuous improvements" were two sub-attributes of the "people" attribute that were not found in the "culture" attribute. However, they corresponded to other key attributes of BIL, such as "customer satisfaction" and "continuous improvements". They were, therefore, not included in "culture and people".

"Contribution by staff at all levels" means employees share their ideas to improve the company's processes, reduce waste, and decentralize decision-making [33]. This can be addressed by applying two major LC techniques, the Last Planner System (LPS) and Pull planning [34]. These two techniques engage staff in planning by specifying their roles and tasks and gradually developing the value delivery process in specific sequences [35]. Adopting BIM provides access to a single source of truth for reference while implementing LPS [36,37].

"Organization training support" makes the individuals fit, qualified, or proficient in a specific task. Locatelli et al. [38] state that training team members is the most important investment when implementing lean construction. Ahmed and Wong argue that there is a need to train staff to be competent in implementing LC by offering government incentives, resolving contract and legal concerns related to the impact of implementing this strategy, and encouraging clients and contractors to invest in adopting the LC procedures [39]. The company has to systematically sustain activities that enrich employees' present knowledge and capabilities for the organization's changing needs. Furthermore, it needs to sponsor the team members and improve communication skills to develop their BIM, IPD, and LC competencies [39].

"Upper-level management buy-in" reflects the degree of management willingness to practice change through BIM, IPD, and Lean execution. The company's top management needs to change employee behaviour and demonstrate a passion for change to implement new approaches [40]. Resistance to change or a lack of readiness from the managerial levels is often a barrier to BIM and IPD implementation [41].

The "early development of project goals" agreed upon and respected by all participants that promote and drive innovation and outstanding performance is critical in IPD projects. According to the IPD guide, it reduces the rework and increases the entire project's value. The emphasis is on jointly fulfilling common goals rather than satisfying personal requirements, which needs the contribution of all construction parties. IPD use strengthens the project team's understanding of the entire supply chain's desired goals early. As a result, it increases the likelihood of the team meeting project objectives, such as schedule, life cycle costs, quality, and sustainability [28]. BIM, suggested as the appropriate technology by AIA, is a tool that can directly contribute to achieving the agreed goal by allowing better integration, cooperation, and coordination [42].

According to the Lean "leadership" style, leaders are coaches instead of controllers. In fact, a leader is the most competent person who sets an example and walks the talk [43]. Early IPD guidelines by AIA suggested that parties assign leadership on a project-by-project basis to the most competent person. However, it should be acknowledged that leaders in any long-term project should be reviewed for team effectiveness by the teams themselves. Leaders who do not reflect the project values must be advised, improved, or removed [44].

The issue of organizational separation is addressed jointly by the IPD and BIM combination [45]. The former facilitates "open and honest communication" among all participants, clearly defined responsibilities, a no-blame culture, and a determination to solve the problem, and the latter facilitates all these by providing a single source of truth [45]. When designers and contractors collaborate intensively in a BIM model as the single source of truth, they share information that enables their partners to better comprehend their expectations and anticipate their actions. In addition, shared BIM models among all parties demonstrate a commitment to one another that can nurture the atmosphere of trust required by the IPD principles.

AIA recommends that individuals and companies should be prequalified for necessary skills, such as BIM skills, and include this in their "hiring policies". Several authors have pointed out the importance of well-educated and competent practitioners utilizing BIM's full potential as an integrated practice [46,47].

According to Dalui et al., the barriers to BIM implementations on IPD projects can be overcome by understanding the project-specified "roles and responsibilities" [48]. Each participant in IPD must have a clearly defined work scope. The IPD project team members ensure that individual participants' tasks and responsibilities are clearly set and understood early [28].

2.1.3. Workplace Standardization

The two LC perspectives reveal the high compatibility of many attributes inside the workplace standardization, such as "5S", "observable process", "VM activities", "defined work process", and "flow of information delivery from start to finish". The detailed analysis of this standardization attribute was inspired by the LC principles illustrated in Figure 5 and broken down for this study into five sub-attributes, including: "Visual Management (VM)", "5S Implementation", "Organization update about the BIM Model", "Just in Time (JIT)", and "Big Room".

"Organizational update on the BIM Model" can ensure that the work process is more transparent and up-to-date for various stakeholders. The "Big Room" also offers a physical environment for monitoring the flow of information and issues by visually displaying the project's status and progress. It is worth mentioning that standardization and waste management have a shared principle under the "Logistic movement and materials plan". It can be linked to JIT as a sub-attribute that eliminates non-value-adding movement and creates an efficient logistical plan.

"Visual Management (VM)" is described as providing project-related information to the staff in an accessible location. Visualizing the project's information and construction processes facilitates the stakeholders' communication, transparency, and self-management capabilities to remove barriers and enhance the extensive flow of information within the workplace [49]. The IPD team member uses VM with easy-to-understand information to keep the project team updated on any BIM model changes, such as library objects or models from other disciplines, on a shared, accessible platform. BIM also provides the ability to visually evaluate the impact of design changes on construction, which is difficult with traditional two-dimensional (2D) drawings. Modeling and animating construction sequences with "four-dimensional" (4D) BIM applications provides a unique opportunity to visualize construction processes and progress, identify resource conflicts, and resolve constructability issues. This enables process optimization, which improves efficiency and safety, and can assist in identifying significant bottlenecks and potential solutions [50].

KanBIM prototype is an example of the BIM-Lean visualization approach; it visualizes on-site process and product status information on BIM models through pulls or signals of the user interfaces, revealing the maturity of scheduled activities and the state of work in progress [51].

The main objective of "Just in Time (JIT)**"** is to provide the right materials or information in the right quantities and quality when it is needed to reduce waste and provide maximum value [52]. BIM can facilitate real-time site coordination, site layout design, site safety and logistics, and the timely supply of materials and equipment. An optimized schedule from the 4D BIM model data with the JIT method enables predicting different scenarios to identify resource conflicts in time and space, minimize costs, and improve safety on construction sites [53]. IPD creates criteria for using relevant and effective information exchange and communication protocols in the BIM Execution Plan to ensure JIT adoption [54].

"Organization update about the BIM Model" on any changes to the BIM model, such as library objects or changed models from other disciplines on a shared accessible platform, is recommended by AIA. It enables the IPD team member to access up-to-date and easy-to-understand information for everyone, with the use of a common language such as IFC (Industry Foundation Class) in the absence of a Common Data Environment (CDE).

The "Big Room" is an important tool that is commonly used in LC and IPD literature. Ma et al. believe that by adopting IPD's "Big Room" technique, the entire project team can be co-located in a Big physical environment where some of the important challenges in design and decision-making, communication, and mismatch between revisions can be minimized [55]. In the "Big Room", the parties are not just meeting together; they are performing their daily work together in cross-functional groups composed of the best-suited individuals drawn from all of the IPD participating firms. They vigorously exchange ideas and perspectives to develop solutions to project issues [56]. A range of traditional communication methods can accomplish synchronous IPD collaboration in a "Big room", such as face-to-face meetings, videoconferencing, as well as advanced platforms such as BIM and complementary mediums such as virtual reality (VR) and augmented reality (AR) [57].

"5S" implementation focuses on developing a culture of cleanliness and standardization, which results in increased safety, space creation, and better teamwork both offsite and on construction sites.

2.1.4. Waste Minimization

LC is considered the best-known approach to reducing waste in the construction industry [58]. The key elements of the Diekmann and Koskela LC waste minimization principles can be summed up as the eight types of LC waste known as "defects". "over-production", "waiting", "non-utilized talents", "transport and motion", "inventory", and "overprocessing and rework" [59] (Figure 6).

Studies show that BIM-based design and construction can effectively contribute to waste minimization [60]. BIM functionalities have improved information exchange with a greater number of project participants, hence accelerating real-time management to support LC principles [61]. Collaboration in design and construction, end-user participation, the use of 4D BIM to reduce process waste, and optimization of the whole system are some of the benefits of IPD and BIM integration, which directly affect waste reduction [26]. BIM supports a Leaner construction process for subcontractors and fabricators by improving cooperation, prefabrication, workflow stability, and inventory reduction. Also, projects using IPD are found to increase productivity and collaboration and reduce waste substantially, thus offering better performance and increasing value for owners, contractors, and designers [28].

A "defect" is an incorrect work that needs to be repaired, replaced, or redone [62]. Igwe et al. defined non-physical defects as inaccurate information on drawings, the creation of substandard work, and failure to meet specifications. The literature explains that the key sources of defects are connected to repetitive design cycles that result from unanticipated changes, poor information management, and communication. BIM offers visualization, clash detection, 4D scheduling, construction sequence planning, and better collaboration to minimize defects. For instance, the clash detection functionality of BIM enhances production control and resolves conflicts early in the design stage to minimize incorrect work and required reworks [63].

"Over-production" refers to producing more material or information than is required or earlier than is necessary. Integrating the chain of customers into the process through IPD can reduce unnecessary activities, so the production chain focuses only on what is requested by the next sequence of clients. Besides, 4D BIM as the facilitator of the necessary determination of the necessary resources for the construction process, including labor, equipment, materials, and space, just at the time of need, is recommended in IPD projects to minimize over-production [64].

"Waiting" happens when any construction party is left waiting for labor, materials, equipment, or Requests for Information (RFI) responses to complete the preceding activity. Applying the Big Room recommended by IPD hand in hand with BIM by implementing a CDE, federated model, and precise program scheduling to ensure timely delivery of information, materials, and equipment can tackle this issue. Four-dimensional-based LPS effectively contributes to reducing the waste of waiting time due to its ability to improve communication in collaboratively planning the network of commitment [65].

"Non-utilized talent" waste happens when companies do not take advantage of the great potential of the available staff's creative ideas and skills [66]. IPD's hiring policies engage "the right person for the right position at the right time", which reduces the number of underutilized employees. Likewise, LC techniques such as LPS and pull planning can minimize the number of unutilized employees by assigning the task to the right employee.

"Transportation and Motion" are the unnecessary movements of materials, equipment, or people that can be avoided using collaborative decision-making techniques and BIM 4D and LC [64]. Modularization and prefabrication are two examples of BIM use that can reduce transportation and unnecessary movement. Accurate quantity take-off using BIM can help calculate the required number of vehicles to avoid unnecessary transportation and motion.

"Inventory" is about providing information, supplies, or items beyond what the various disciplines require [67]. Automated multidisciplinary design review with BIM in an IPD environment where disciplines (civil, mechanical, electrical, architectural, etc.) collaborate intensively results in less on-site waste and extra information. It also contributes to the "Extra Processing" waste type by minimizing unnecessary steps with the intention of providing higher-quality products than necessary and producing to standards beyond specifications.

"Rework" relates to coordination and administrative workflows on a construction project, leading to double data entry. Eliminating paperwork with blueprint software and having a single source of truth, such as a BIM model, will ensure a reliable flow of information and keep project teams on the same page about the workflow and infor-mation. It helps the teams discover the errors early and avoid rework [68,69]. Likewise, rework associated with design changes can be minimized by early client engagement using a detailed building model [70].

2.1.5. Continuous Improvement (CI)

"Continuous improvement" includes four sub-attributes: "Metrics", "Error Proofing", "Response to Defects", and "Organizational Learning". Each of these sub-attributes contributes to the idea that the achievement of this near-perfection should be a continuous endeavor [71]. Given the information in Figure 7, "Organization learning" and "defect root cause identification" were incorporated in this research by the "Plan-Do-Check-Act (PDCA)" sub-attribute, which refers to the company's assimilation and transfer of information and lessons learned to facilitate continuous process improvement [72]. In addition, as "CI responsibility" was previously allocated under the "culture and people" attribute, it was not reused in the CI structure.

"Metrics" are used to monitor and improve all project processes, which must be consistent throughout time and simple for all staff to read and understand. According to the AIA IPD guide, project performance is no longer measured solely by traditional cost, schedule, and scope but also by other metrics agreed upon by all parties. Financial incentives may also be attached to the parties' achievement of specifically agreed metrics [28]. The IPD project plan includes project metrics, values, and reporting intervals to monitor the project's progress. In these projects, the owner participates in establishing project metrics at an earlier stage than in traditional project contracts [28]. BIM and LC techniques are employed in the IPD environment to fulfill the agreed metrics.

"Error-proofing" is the process of proactively eliminating errors from work. These precautions, by their nature, are proactive instead of reactive. BIM-related examples include the existence of a BIM champion or a quality plan that defines the roles and responsibilities of the individuals involved in each given project. In the case of a work defect, crews, individuals, and IPD parties behave in accordance with this quality strategy [73].

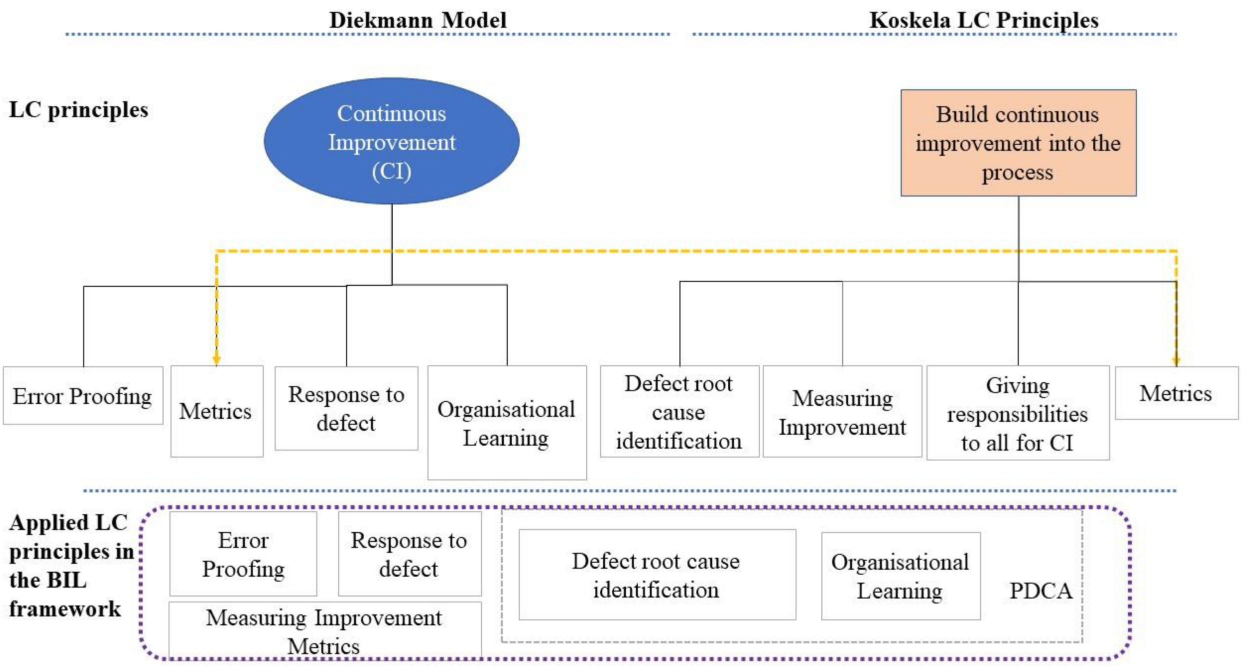

Figure 7. Diekmann and Koskela's LC principles [16,17]-Continuous Improvement.

"Response to defects" refers to the effective management of problems and the retention and documentation of the identified solutions for future use. BIM, for instance, enables the stakeholders to conduct a virtual Gemba (go and see yourself) using software such as Navisworks to find potential clashes and problems before they happen in construction [2]. In this sense, virtual walks on detailed BIM models are a more convenient option for busy or remote managers. Managers can use this BIM functionality to document and keep track of issues and solutions for future reference.

To implement CI, companies adopt "PDCA" to solve both unit-functional and cross-functional problems in their activities. The Plan stage aims to achieve a balance between opportunities (design, materials, equipment, work fronts) and priorities (deadlines, dependencies, resources, costs) to encourage a pulled production system of the activities in order to achieve an optimum level of production. In this stage, the technical feasibility of the work package is evaluated. Do refers to task execution control considering supply, production, quality, health, safety, and the environment. Check analyses of the results and metrics related to physical and financial advancements, key performance indicators, issues, and problems, and Act evaluates the greatest optimal opportunities based on the relationship between expected and actual results. [74]. BIM's data storage and sharing ability enable learning from past projects to improve the practices in future projects. The outcomes and obtained data can be assessed by the IPD parties to resolve the issues in the project.

2.2. *Delphi Method*

The Delphi method has been widely used in construction research to address complex problems where there is not a strong body of knowledge and to provide solutions by recruiting knowledge-related experts and soliciting their opinions [75]. The Delphi method is an anonymous reiterative method with controlled feedback after completing each round and then applying statistical group response analysis. The primary objective of Delphi is group communication that seeks to achieve opinion convergence. The anonymity of the responses enables participants to provide honest answers without concern for judgment by their peers. The most common number of rounds to reach a consensus in Delphi studies is usually two or three [76]. Nevertheless, some studies argue that consensus-building may occasionally require four or even five rounds [18].

The Delphi survey questionnaire was designed in this study in accordance with the attributes obtained from the literature. It included Likert-scale and open-ended questions to collect quantitative and qualitative data. Open-ended questions were also added to enable the panel to add or remove any attribute or add their feedback on the questioned attributes. On the five-point scale (from 0-strongly disagree at all to 5-strongly agree), Likert questions were used to (a) measure the suitability of the recommended attributes and (b) assess the level of consensus.

Before starting the Delphi study, four academic experts reviewed the questionnaire for consistency and completeness through a pilot study. A number of subsequent changes were made based on feedback on the initial BIL framework, such as rephrasing a few attributes and modifying their descriptions. For example, the "clients' need" and "training" terms were respectively rephrased as "recognition of the entire supply chain as a client chain" 'and "organizational training support". Finally, between October 2021 and January 2022, two online Delphi rounds were conducted.

A systematic review of the Delphi method revealed that a panel size of 7–20 is recommended in construction engineering and management research [77–80]. According to Gluszek [81], the inclusion of the small panel size is crucial to avoid experts' frequently high dropout rate in successive Delphi rounds, which has been observed as common in larger groups with more than 20 members. As a result, the research team reached out and emailed more than 100 survey invitations. After two months and a number of follow-ups, the first Delphi round was initiated upon receiving 15 acceptances. This number also exceeded the minimum number of participants in the Delphi studies. The experts were selected from diversified roles and disciplines, such as construction managers, architects, BIM managers, quantity surveyors, policymakers, etc., with at least eight years of experience in managerial roles. All these experts had extensive leadership experience in the construction industry, implementing BIM, LC, and IPD with a strong knowledge of their interrelationships (Table 1).

Before commencing the first round, the experts were provided with a brief overview of the BIM-IPD-LC maturity study. The questionnaire was distributed via the Qualtrics platform. To reduce the possibility of misinterpretation, the survey also contained pop-up boxes with detailed descriptions of attributes drawn from the literature. Experts were asked to evaluate the significance of the five main attributes and 26 sub-attributes. They were required to demonstrate to what extent they agree that the key principles of Lean construction can be included in the BILMM key attributes. Then, they were asked whether the proposed sub-attributes could support the corresponding attribute in the maturity framework. An example of the Delphi questionnaire is displayed in Appendix A. By the end of Round 1, qualitative and quantitative data were analyzed and used to modify the initial framework.

The Delphi method's quantitative results can be analyzed regarding the analytical statistics and the consensus levels. The mean value and Standard Deviation (SD) are the most common analytical statistics and were calculated to evaluate the level of importance of attributes and sub-attributes [82] (Table 2). According to the literature, an SD below 1 in a five-point Likert-scale questionnaire is mainly accepted as a low dispersion level in the rating [83]. SD was found lower than 1 for most attributes and sub-attributes, except "defect", "over-production", "waiting", "non-utilized talents", "transportation and motion", and "inventory and rework", which are all associated with the waste minimization attribute. SD for JIT attributes was 1.39, over the expected SD. The mean value is also used to determine the importance of attributes and sub-attributes. The higher mean value reflected the greater significance of an attribute from the perspective of the experts. The mean value results showed that the "optimizing value" and "early goal definition" were the most significant among other sub-attributes.

Table 1. Background information of the Delphi participants.

Participants	Profession	Years of Experience	Expertise Area	Type of Organization
R1	Civil Engineer	10	BIM, LC	A large business
R2	Continuous improvement lead	18	Lean, IPD	A large business
R3	Digital engineering project manager	9	BIM, IPD, LC	A large business
R4	BIM and digital engeeing manager/ Academic	17	BIM, LC, IPD	A large business
R5	Academic/ Construction and project manager	20	BIM, MM	A large business
R6	Quantity surveyor/ Constructors association executive	30	LC, IPD	A micro-business
R7	Building Engineer/ Academic	8	BIM, IPD	A large business
R8	Mechanical engineering director	25	BIM, IPD	A small business
R9	BIM/computation lead	10	BIM, IPD	A large business
R10	Architectural Design manager	30	BIM	A large business
R11	Digital technologies manager	39	BIM, IPD	A medium business
R12	Architect/Director	19	BIM	A large business
R13	Digital engineering director	11	BIM, IPD, LC	A large business
R14	BIM Consultant	10	BIM, IPD, LC	A large business
R15	Construction manageer	19	BIM, LC	A small business

Note: R = Respondents.

Two techniques for calculating levels of agreement were used: the overall agreement (OA) and the stability tests on experts' responses using Kendall's coefficient of concordance (W). The analysis of the OA in the first round showed that even though it was more than 50% (OA) for all attributes, SD values over 1.0 for a number of attributes necessitated conducting the second round.

In Round 2, the same panelists were employed. Even though 13 out of 15 experts agreed to re-evaluate the BIL maturity framework, the number of participants remained within the range required for Delphi studies. The distributed questionnaire was mainly similar to Round 1, with some changes incorporating learnings from the previous round. Waste minimization sub-attributes were adjusted based on the expert's input and further literature analysis to make the associated sub-attributes more precise. Since the primary objective of the Delphi method is to reach a rigorous consensus, the authors provided quantitative and qualitative data regarding the opinions of other panel members to revise their initial judgments until an agreement was achieved. As a result, a controlled feedback survey was provided for the second Delphi round, including a summary of statistics on the experts' overall agreement from the previous round, descriptive comments, and the refined BIL framework. Additionally, an Excel sheet was personalized for participants to include their previous responses in Round 1 for comparison of the aggregated responses of the panelists to each question. This technique encouraged panelists to reassess their initial BIL assessments and reach a group consensus.

Table 2. Delphi Round 1 Results.

Attribute	M	SD	OA	A	SA		Sub-Attribute	M	SD	OA	A	SA
Customer focus	4.21	0.94	64.28%	7.14%	57.14%	1.	Flexible resources	3.86	0.83	71.43%	50.00%	21.43%
						2.	Optimizing value	4.79	0.41	100%	21.43%	78.57%
						3.	Recognition of the entire supply chain as the client	4.64	0.61	92.86%	21.43%	71.43%
Culture and people	4.43	0.73	85.71%	28.57%	57.14%	4.	Contribution by staff at all levels	3.86	0.99	70.88%	42.86%	28.57%
						5.	Organization training support	4.29	0.7	85.72%	42.86%	42.86%
						6.	Upper-level management buy-in	4.64	0.61	92.86%	21.43%	71.43%
						7.	Early goal definition	4.71	0.59	92.86%	14.29%	78.57%
						8.	Organization hiring policies	3.5	0.5	50.00%	50.00%	0.00%
						9.	Open communication	4.5	0.63	92.85%	35.71%	57.14%
						10.	Leadership	4.5	0.63	92.85%	35.71%	57.14%
Workplace standardization	4.57	0.62	92.86%	28.57%	64.29%	11.	Visual management	4.29	0.8	78.57%	28.57%	50.00%
						12.	5S implementation	3.86	0.74	64.29%	42.86%	21.43%
						13.	Organization updates about the BIM Model	4.07	0.88	64.29%	21.43%	42.86%
						14.	Just in time	3.71	1.39	71.42%	35.71%	35.71%
						15.	Big Room	3.93	0.8	64.28%	35.71%	28.57%
Waste minimization	4.43	0.73	85.71%	28.57%	57.14%	16.	Defect	4.14	1.12	78.57%	28.57%	50.00%
						17.	Over-Production	3.71	1.33	71.42%	35.71%	35.71%
						18.	Waiting	3.64	1.11	64.29%	42.86%	21.43%
						19.	Non-utilized talents	3.75	1.09	66.67%	41.67%	25.00%
						20.	Transportation and motion	4.00	1.07	78.57%	42.86%	35.71%
						21.	Inventory	3.79	1.15	57.14%	21.43%	35.71%
						22.	Extra processing (Rework)	4.14	1.12	78.57%	28.57%	50.00%
Continuous improvement	4.36	1.11	85.72%	21.43%	64.29%	23.	Metric	4.43	0.62	92.86%	42.86%	50.00%
						24.	Responses to defects	4.29	0.88	71.43%	14.29%	57.14%
						25.	Error proofing	4.00	0.76	71.43%	42.86%	28.57%
						26.	PDCA implementation	4.29	0.8	78.57%	28.57%	50.00%

Notes: M = Mean, SD = Standard Deviation, OA = Overall agreement, Agree, A = Agree, SA = Strongly.

Table 3 lists the Round 2 results. The Standard Deviation dropped in all attributes and sub-attributes, indicating an increase in consensus. Kendall's W value was calculated in two distinct ways to ensure that both methods offered high levels of consistency. Kendall's W value ranges from 0 (no agreement) to 1 (total agreement), with any value above 0.7 indicating a high level of agreement. In this study, the W values for the mean values and the percentage of overall agreement between rounds are 0.805 and 0.858, respectively, confirming the participants' high level of consensus [84]. As a result, the research team concluded the Delphi rounds since

a. There were less than 15% changes in the levels of consensus, which was a sign of ending the Delphi rounds [85];
b. Most of the BIL maturity sub-attributes reached a specific agreement on their level of importance [71];
c. The high stability of Kendall's W between rounds indicated that repeating Delphi rounds would not contribute further to this study.

Table 3. Delphi Round 2 Results.

Attribute	M	SD	OA	A	SA	Sub-Attribute	M	SD	OA	A	SA
Customer focus	4.38	0.74	84.62	30.77%	53.85%	1. Flexible resources	4.23	0.58	92.31%	61.54%	30.77%
						2. Optimizing value	4.77	0.42	100%	23.08%	76.92%
						3. Recognition of the entire supply chain as the client	4.54	0.63	92.31%	30.77%	61.54%
Culture and people	4.31	0.72	84.61	38.46%	46.15%	4. Contribution by staff at all levels	4.08	0.62	84.62%	61.54%	23.08
						5. Organization training support	4.38	0.62	92.3%	46.15%	46.15%
						6. Upper-level management buy-in	4.69	0.61	92.3%	15.38%	76.92%
						7. Early goal definition	4.31	0.72	84.61%	38.46%	46.15%
						8. Organization hiring policies	3.46	0.63	38.46%	30.77%	7.69%
						9. Open communication	4.62	0.49	100%	38.46%	61.54%
						10. Leadership	4.77	0.58	84.62%	7.69%	84.62%
Workplace standardization	4.38	0.62	92.31	46.15%	46.15%	11. Visual management	4.46	0.63	92.31%	38.46%	53.85%
						12. 5S implementation	4.00	0.78	69.23%	38.46%	30.77%
						13. Organization updates about the BIM Model	3.92	0.73	69.23%	46.15%	23.08%
						14. Just in time	4.00	0.96	69.23%	30.77%	38.46%
						15. Big Room	3.85	0.53	76.92%	69.23%	7.69%
Waste minimization	4.54	0.63	92.31	30.77%	61.54%	16. Defect	4.15	0.77	76.92%	38.46%	38.46%
						17. Over-Production	4.62	0.49	100%	38.46%	61.54%
						18. Waiting	4.00	0.78	69.23%	38.46%	30.77%
						19. Non-utilized talents	3.62	0.74	46.15%	30.77%	15.38%
						20. Transportation and motion	4.23	0.70	84.61%	46.15%	38.46%
						21. Inventory	4.23	0.89	69.23%	15.38%	53.85%
						22. Extra processing (Rework)	4.69	0.46	100%	30.77%	69.23%
Continuous improvement	4.54	0.63	92.31	30.77%	61.54%	23. Metric	4.31	0.61	92.31%	53.85%	38.46%
						24. Responses to defects	4.38	0.62	92.31%	46.15%	46.15%
						25. Error proofing	4.23	0.58	92.31%	61.54%	30.77%
						26. PDCA implementation	4.54	0.75	84.61%	15.38%	69.23%

Notes: M = Mean, SD = Standard Deviation, OA = Overall agreement, Agree, A = Agree, SA = Strongly.

3. Discussion

This research contributes to the current literature on BIM, IPD, and LC integration attributes in the context of MMs. The proposed framework provides valuable insights for academics and industry practitioners seeking to improve their understanding of BIM, IPD, and LC interdependencies. Furthermore, the findings confirm the formulated hypothesis: "BIM and IPD can support the implementation of LC principles, and their interdependencies can serve as the basis for an integrated maturity framework structure". The Delphi participants evaluated and confirmed the hypothesis in the Likert scale questionnaire and the descriptive comment.

The results of this study were compared to other BIM, IPD, and LC maturity-related studies. The proposed framework was considered comprehensive because it is built upon an extensive review of the related literature and experts' validation through two Delphi rounds.

Based on expert opinion, the suggested set of main attributes for the MM structure largely complied with Diekmann's LC principles and Koskela's theory of LC and associated principles. In addition, the participants agreed significantly that the key LC principles could serve as the BIL Maturity Framework key attributes. The importance of these attributes has been evidenced by the high percentage of OA, which is over 80% in both Rounds and for almost all of the key attributes.

Findings, however, emphasize the uniqueness of the BIL framework's attributes from these two references due to the novelty of this framework in integrating BIM, IPD, and LC. In this study, Diekmann and Koskela's principles complement each other and are the point of departure in developing the BIM-IPD-LC framework. The attributes were further broken down to demonstrate the detailed level of dependency and relationship between BIM, IPD, and LC, which were missed in the previous maturity models. For example, no precise definition for the "customer" or "client" exists in any related MM literature. In this study, however, both external and internal customers are reflected in the "Recognition of the entire supply chain as a client chain" attribute. From a participant's viewpoint, it was suggested that in relation to "Recognition of the entire supply chain requirements", the attribute can be more granular and include definitions of requirements such as Employers' Information Requirements (EIR), Organizational Information Requirements (OIR), Asset Information Requirements (AIR), Project Information Requirements (PIR), and Exchange Information Requirements (EIR).

The most significant outcome of Delphi Round 1 was that the main attributes and sub-attributes received more than 50% of the respondent's overall agreement. The most significant finding in Round 2 was a shift in the panel's perceptions of sub-attributes such as "hiring policies" and "unutilized talent". A surprising finding in comparison with existing literature was the elimination of "hiring policy", which reached only 50% in the first round and 38% overall agreement in the second, despite assertions that this is an IPD principle in the questionnaire. It is worth further investigation as to whether this may be more important in relation to establishing IPD principles in an organization. As a result, the phrase "hiring policy" was removed from the list.

Due to the absence of a comprehensive description of the MMs' design procedures, the level of model uptake is observed to be low [86]. Nonetheless, this work has analyzed the interdependencies of BIM, IPD, and LC in-depth in order to present a comprehensive list of MM attributes with a clear design approach. In the majority of related MMs, particularly BIM MMs with a greater number of publications and a more rigorous theoretical foundation, the emphasis has been placed on the organization's processes, information, and overall technological maturity in BIM adoption [87]. However, the BIL maturity framework indicated that embracing collaborative approaches necessitates the effective implementation of LC and IPD in addition to BIM implementation.

Organizational culture and the role of people have not been included in most BIM MMs, which can be gained by incorporating LC. However, the culture/people attribute derived from the Delphi Rounds places significant emphasis on staff involvement at all levels, using pull planning where possible. It is only observed in a BIM MM developed by Sieblink [12], in which "people and culture" are two primary attributes. Nevertheless, the BIL maturity framework not only incorporates the above-mentioned BIM MM "people and culture" sub-attributes but also provides a broader range of sub-attributes, including "organization training support", "upper-level management buy-in", "early goal definition", "open communication", and "leadership" that have been agreed upon by more than 80% of respondents.

Standardization through "visual management", "5S implementation", "Organization updates about the BIM Model", "Just in time", and "Big Room" have gained the experts' consensus as these Lean techniques could be strongly supported and implemented by BIM and IPD integration. It again stresses the uniqueness of this study to look at the proposed LC techniques from a new viewpoint. All these LC techniques are validated with the expert's feedback, while the way these techniques can contribute to the BIL framework is less studied and validated by experts' opinions in other models.

Most panel members had a significant agreement on waste minimization in the second round and its sub-attributes; however, "non-utilized talent" was excluded from the list as it only received 46% of the overall agreement.

In the iterative rounds of Delphi, the wording of several attributes was modified based on the panel's recommendations. The qualitative analysis of the experts' comments also confirmed the robustness and appropriateness of the selected attributes. For instance, according to a participant, "a BIL cannot succeed without having continuous improvement in mind. This will be grown with the support of the organization's culture and staff. Also, the customer has to be always in focus from the first stage". From a different viewpoint, it was asserted that "The reason I strongly agree with most of the sub-attributes is that if one of them is neglected, then the implementation process will be hindered and unsuccessful." This is very consistent with the literature's suggestions for integrating BIM, IPD, and LC so that all three can function collaboratively to achieve their fullest potential.

4. Conclusions and Future Work

This research contributes to the literature by investigating the interrelationships between BIM, IPD, and LC and formulating a set of attributes that will serve as a point of departure for the development of a BIL MM. In addition, it serves as a comprehensive reference guide on the BIL competency structure for construction practitioners who aim to further apply and invest in this synergy. The BIL framework is intended to be further expanded into a BIL maturity model, eventually leading to a BIL implementation roadmap and benchmarking method for planning future objectives and assessing an organization's current status.

An extensive literature review was used to develop a comprehensive BIL framework with five main attributes and 26 sub-attributes. It was then evaluated and verified using the Delphi method, which resulted in the removal of two sub-attributes and the refinement of the BIL's framework structure to five major attributes, with 24 sub-attributes remaining on the list. In this regard, the findings support the critical contribution of the extracted attributes and most sub-attributes from the literature review round.

"Optimizing value" is the only sub-attribute that gained 100% overall agreement in both Rounds. This highlights the significance of value generation in construction projects from an academic and professional perspective using BIM and IPD. The percentage fluctuation in the attributes between the results of the two Rounds varied. The OA in most attributes did not change considerably, except for "overproduction", "responses to defects", "customer focus", "flexible resources", and "visual management", which had more than a 20% difference in two Rounds. This is mainly due to the attributes being revisited based on the results of the first round and applied in the redevelopment of the Delphi 2 questionnaire. The Delphi process stopped in the second round after achieving convergence, and 24 sub-attributes were established for this framework.

These results provide future researchers with information about the barriers that prevent BIL from being widely used and for them to propose possible solutions. The breadth and depth of interconnections between BIM, IPD, and LC imply that construction companies on a Lean journey should seriously consider using BIM and IPD to enhance Lean outcomes and smooth transitions in LC implementation.

This study also has some limitations that can provide direction for future research. First, the empirical data used in this study were collected within the Australian construction industry, with its specific institutional and cultural context, so we are limited in generalizing our findings to other institutional and cultural contexts. Future studies can be conducted to test the model's validity in real-world projects. The proposed framework is a starting point for future studies aiming to establish the structure for an integrated BIM, IPD, and LC MM. Our prospective research will focus on applying the BIL framework to developing a BIL MM.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. The Delphi Survey Questionnaire Example

Q2. To what extent do you agree that the following Lean Construction principles can be incorporated into the BIL MM as the point of departure?

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
Customer focus	○	○	○	○	○
Culture & people	○	○	○	○	○
Workplace standardization	○	○	○	○	○
Waste minimization	○	○	○	○	○
Continuous improvement	○	○	○	○	○

Q3. Please add your comments and/or any further sub-attributes which have been missed in the previous section.

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