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Network-Based Modeling of Lean Implementation Strategies and Planning in Prefabricated Construction

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Abstract: Prefabricated construction (PC) is increasingly promoted in the construction sector for its potential benefits, including reduced resource assumption and improved quality. Accordingly, Lean methods are popularly applied to PC projects for optimizing operational processes and enhancing their performance in line with strategic objectives. A key factor in effectively implementing Lean to improve strategic control is developing specific strategies and planning that consider their complex interactions. Thus, this paper aims to propose a quantitative network-based model by integrating Interpretive Structural Modeling (ISM) and Matrix Impact Cross-Reference Multiplication Applied to a Classification (MICMAC) under complex network theory to develop a Lean implementation framework for effective strategy formulation. Specifically, 17 Lean implementation strategies for PC in the context of the Chinese prefabrication industry were identified via an extensive literature review and expert interviews. Then, ISM-MICMAC quantitatively identifies the direct and indirect relationships among strategies, while subsequent analysis of Topological Structure Weight (TSW) and Structural Degree Weight (SDW), as complex network parameters, is used to evaluate the importance of each strategy. The findings show that the strategic planning for Lean implementation in PC consists of four levels, i.e., foundation, organizational, technical, and control. Selecting appropriate Lean tools and technologies is crucial for PC implementation, which must be built on a top-level management team and foster a Lean culture. Moreover, it involves building a standardized system of processes and activities, enhancing both internal and external collaboration, and continuously improving processes in response to changes. On one hand, this in-depth network-based analysis offers practical insights for PC stakeholders, particularly in China, on Lean implementation in line with PC performance and strategic control and objectives. On the other hand, the network-based model can be future-implemented globally. Additionally, this study expands the current body of knowledge on Lean in PC by exploring the interrelationships of Lean implementation strategies.

Keywords: prefabricated construction; Lean implementation; strategy planning; ISM-MICMAC; complex network

Citation: Dang, P.; Geng, L.; Niu, Z.; Jiang, S.; Sun, C. Network-Based Modeling of Lean Implementation Strategies and Planning in Prefabricated Construction. *Buildings* **2024**, *14*, 3182. https://doi.org/10.3390/buildings14103182

Academic Editors: Wenzhe Tang, Wenxin Shen and Jin Xue

Received: 5 September 2024
Revised: 25 September 2024
Accepted: 2 October 2024
Published: 6 October 2024

1. Introduction

Prefabricated construction (PC), characterized by standardized design, factory production, on-site assembly, and life-cycle data management [1] is a sustainable approach with a great increasing popularity. For example, the Ministry of Housing and Urban–Rural Development of the People's Republic of China (MHURD) has aimed to develop PC to comprise over 30% of all new buildings by 2025 [2]. It differs from traditional in situ cast construction, where the operation management of internal and external processes and the overall supply chain play a crucial role in determining project performance [3]. In this context, Lean has been particularly effective, demonstrating substantial improvements in industrial chain management, strategic management, construction capabilities, and overall project performance [4–7]. It refers to the tools and practices for precisely defining value, reducing unnecessary interference to increase efficiency, doing more and more with less and less to gear products more towards user needs, and eliminating waste while creating value [8]. The effective implementation of Lean needs an applicable planning comprised of implementation strategies that reflect the socio-cultural and operational contexts, which will serve as a guideline to identify relevant Lean practices and specify step-by-step procedures to implement Lean in line with PC performances and strategic missions and objectives [9,10].

However, ignoring the interrelationships among Lean implementation strategies primarily leads stakeholders in PC to fail the effective implementation of lean [11]. Particularly speaking, Lean implementation can be seen as a systematic engineering involving multiple strategies and factors [12,13]. These strategies are not isolated but are interacted in complex interactions, significantly impacting the effectiveness of their implementation. It demands that stakeholders in PC develop systematic strategies following a certain plan rather than merely applying Lean tools and methods [11,14]. Therefore, it is imperative to construct a plan for Lean implementation by thoroughly exploring the interrelationships between Lean implementation strategies.

Current research has proposed a series of methods to explore the interrelationships among strategies, including Factor Analysis (FA), Analytic Network Process (ANP), Structural Equation Modeling (SEM), and Interpretive Structure Modeling (ISM) [15]. Among them, ISM is considered particularly effective for depicting the mutual relationships and hierarchical structures between various factors [16]. It is often integrated with Matrix Impact Cross-Reference Multiplication Applied to a Classification (MICMAC) to more clearly and quantitatively describe the relationships and their effects on project implementation [17]. To effectively formulate the planning of Lean implementation, it is vital to determine the importance of these strategies within the complex system as well, which not only recognizes their relative importance but also considers their interacted structures. Complex network theory is therefore well-suited for exploring characteristics such as Topological Structure Weight (TSW) and Structural Degree Weight (SDW) in complex systems composed of nodes with intricate interactions [18]. Consequently, a systematic and quantitative network-based ISM-MICMAC model is developed to explore structural and mutually influential interrelationships among Lean implementation strategies, further formulating a plan for Lean implementation for PC.

The objectives of this study are: (1) identifying Lean implementation strategies for advancing prefabricated construction (PC); (2) quantifying the direct and indirect relationships between these strategies; and (3) exploring their priorities. This will facilitate the effective implementation of Lean practices within PC contexts through an innovative network-based analysis of interrelationships among Lean strategies. Moreover, this study not only applies existing theories of Lean, PC, ISM-MICMAC, and complex network theory but also contributes theoretical enrichment to the field of project management.

2. Literature Review

2.1. Lean Implementation Strategies

Current research has focused on how to effectively implement Lean in the construction sector from various perspectives, regarding influencing factors, obstacles, challenges, and strategies [8,19–21]. For example, Yunus et al. [13] identified 31 key factors for implementing Lean in Malaysian Industrialized Building Systems, particularly on management support, process management, and education and training. Similarly, Hussein and Zayed [11] employed meta-analysis to determine the top seven influential factors in modular construction projects, with respect to management, technology, culture, knowledge, finance, government, skills, logistics, and communication. For obstacles or challenges in implementing Lean, Mano et al. [22] identified 83 obstacles and determined eight key obstacles involving culture, leadership, and structure in Lean construction. These types of studies have laid the groundwork for developing appropriate Lean strategies. For instance, Ahmed et al. [20] proposed Lean implementation strategies to enhance the level of Lean implementation by identifying the main 41 challenges. In earlier 2015, Bashir et al. [23] proposed 13 Lean implementation strategies by identifying implementation obstacles in the UK construction industry.

These previous studies enable stakeholders to understand the key elements of successful Lean implementation in PC projects. However, they have paid less attention to examining the full perspective of implementation frameworks for Lean strategies, with a few studies shedding light on this aspect. For example, Gao and Low [12] proposed a four-tier Lean implementation framework based on 14 principles of the "Toyota-way" model, involving philosophy, process, people, partners, and problem-solving aspects. Despite the pilot conceptual frameworks, there is a lacking specific Lean implementation framework, focusing on strategy planning for PC, especially in the context of China. Moreover, the interrelationships between Lean implementation strategies are ignoring [11]. This limits potential process management and improvement of PC projects through Lean. In fact, the successful implementation of Lean is systematic engineering. On one hand, the implementation strategies are interconnected. Neglecting these interrelationships means stakeholders cannot formulate effective Lean planning and strategies [3]. On the other hand, Lean not only focuses on the selection of tools and technologies but also needs to address the current demands of construction projects and the industry.

2.2. Models for Interrelationships Analysis

In recent years, researchers from the construction management field have focused on exploring the interrelationships among factors or strategies and their impact on project implementation. Several quantitative models have been proposed [15,24,25], including but not limited to FA, ANP, SEM, and ISM. Among of them, FA, ANP, and SEM primarily focus on classifying factors but fail to further break them into a logically progressive hierarchical structure based on their interrelationships [26,27]. Notably, ISM is seen as an effective method for clearly depicting the interrelationships and hierarchical structure among factors, which is widely used in systems engineering and particularly suitable for system analysis involving numerous variables, complex factor relationships, and unclear hierarchical structures [24,28,29]. It helps simplify complex systems and assists in identifying the structure within the system [30]. This is because it not only establishes direct and indirect relationships among factors but also identifies the extent of their impact on the target, thereby facilitating the formulation of effective implementation plans [31].

Notably, when exploring structural relationships among factors using ISM, it is often integrated with MICMAC model [17,32]. This integrated ISM-MICMAC model provides a precise depiction to validate the factors and their relationships, as well as the roles of different factors in ISM, thus promoting subsequent clearer planning measures [33–35]. For example, Gan et al. [36] used ISM to explore the interrelationships among barriers to the transformation of the Chinese construction industry towards PC and further utilized MICMAC to classify these barriers to identify the key barriers. This integrated model provides insight into how these barriers influence one another, with the potential for future research to quantify these interrelationships on a larger scale. Then, Sarhan et al. [10] employed ISM-MICMAC to develop a Lean implementation framework for Saudi Arabia's construction industry. The ISM technique in this study was to specify the hierarchical relationships among the 12 critical success factors that contribute to the successful implementation of Lean construction. From these studies, the ISM-MICMAC model has been validated as an effective tool for understanding the relationships among numerous elements within a system by developing a structured model of these relationships [37,38]. This helps to impose order on and direction to the relationships among elements in a system, such that their influence can be analyzed.

Despite its merits, this ISM-MICMAC model is criticized for overlooking the relative importance among factors [39]. Put another way, the interrelationships among Lean implementation strategies are complex and multifaceted [40]. In such a complex network structure, the degree of connection, the position of strategies, and interactions have a significant impact on the importance of strategies. For instance, Wang et al. [41] have considered the impact of out-degree, in-degree, and network hierarchy of nodes on the importance of nodes. In the ISM-MICMAC model of Lean strategies, there are both driving and dependent strategies. Therefore, their importance is not only related to adjacent strategies but also connected to strategies with indirect relationships. However, existing ISM-MICMAC studies paid less attention to this aspect. Complex network methods are thus introduced owing to their advantages in both focusing on the relative importance of factors and exploring the impact of the structural characteristics of complex networks on factor significance [42]. The mutual relationships between nodes and their importance can be determined through topological structure parameters within complex networks [43].Regarding this, TSW is a favorable parameter used in complex network analysis to assess the relative importance of nodes [44]. It evaluates the contribution of a node based on its position in the overall network topology. In studies involving network theory, TSW is often used alongside other metrics, like SDW, to provide deeper insights into the hierarchical and relational structure within the network. Liu and Xu [45] have combined the ISM with the complex network method to identify critical factors in manufacturing systems. However, they did not conduct MICMAC analysis for the path analysis.

Therefore, this paper integrates a network-based ISM-MICMAC model to systematically explore the interrelationships of the strategies and their relative importance to developing the Lean implementation framework. This aims to help stakeholders in PC develop more effective Lean strategies and paths, thereby enhancing strategic control and project performance.

3. Methodology

The four-step research design is presented as Figure 1.

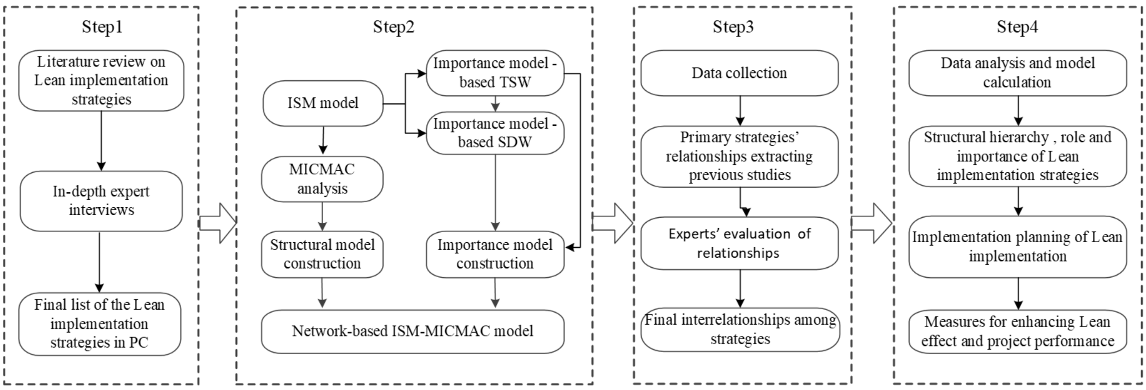

Figure 1. Research design for Lean planning.

3.1. Identifying the Lean Implementation Strategies

Firstly, a list of Lean implementation strategies in PC was identified via a detailed literature review and further examined through in-depth expert interviews to obtain the final list. Two rounds of literature review were conducted to identify potential Lean implementation strategies. The literature databases include global databases, i.e., "Google Scholar", "Web of Science", "Scopus", and Chinese databases such as "CNKI to include full relevant sources. The 1st round of searching criteria was set as Title/Abstract/Keyword = ("lean" OR "just-in-time") AND ("prefabricated construction" OR "prefabrication" OR "precast" OR "off-site construction" OR "industrial building system") AND ("strategies") with no time limitations. As peer-reviewed papers follow a rigorous review process as compared to the conference papers, document type was set to Article, and language was set to English. Only about 20 journal papers are retrieved, indicating that research on Lean implementation strategies in PC is relatively limited. Then, the 2nd round of literature review mainly involves expanding keyword searches, as the successful implementation of Lean is also related to various factors, including barriers, risks, drivers, or challenges. The searching criteria was reset as Title/Abstract/Keyword = ("lean" OR "just-in-time") AND ("prefabricated construction" OR "prefabrication" OR "precast" OR "off-site construction" OR "industrial building system") AND ("strategies OR "factors" OR "barriers" OR "risks" OR "drivers" OR "challenges"). This search brought forth nearly 100 papers at first, after excluding duplicates. Next, the papers went through visual filtering: the Abstract was scanned to remove irrelevant studies. Finally, there were 25 publications remaining for a full-text review, which detailed the specific strategies, factors, barriers, risks, drivers, and challenges of implementing Lean. Based on their frequency of occurrence and importance, 33 Lean implementation strategies in PC are identified, which are mentioned more than 3 times. These strategies refer to four aspects of process: technology, organization, and culture [11,46].

Then, in-depth experts' interviews with key stakeholders in PC were conducted to examine the comprehensiveness and effectiveness of the 33 strategies from the literature. The key stakeholders in PC are consisted of developer, designer, producer, general contractor, subcontractor, supplier, and PC consultant [2,47]. The interviewees were selected and invited according to the stakeholder-based sampling principle: (1) with sufficient knowledge regarding Lean implementation and more than 5 years of related experience; (2) having undertaken important tasks of implementing Lean in PC projects; (3) holding senior positions in the project teams [48]. These principles can ensure that the selected interviewees are qualified to answer the questions pertaining to the Lean implementation strategies to ensure validity and accuracy. Interviewees were recommended by the MOHURD and contacted whether they could be participants via email or telephone [47,49]. A total of 30 interviewees who met the selected principles were selected, which consisted of 5 developers, 3 designers, 5 producers, 5 general contractors, 4 subcontractors, 3 suppliers, and 5 PC consultants. Table 1 shows the interviewee profiles.

Table 1. Interviewee profiles.

Stakeholder Group	Number	Main Position	Education Level	Years of Experience
Developer	1	General manager	Ph.D.	≥5
	4	Business manager	Master	
Designer	3	Business manager	Master	≥5
Producer	1	General manager	Ph.D.	≥5
	4	Factory manager	Master	
General contractor	2	General manager	Master	≥5
	3	Project manager		
Subcontractor	1	General manager	Bachelor	≥5
	3	Project manager		
Supplier	1	General manager	Master	≥5
	2	Business manager	Bachelor	
PC consultant	2 3	Professor Project manager	Ph.D. Master	≥5

Prior to the interviews, research background and purpose were sent to each interviewee via email. After obtaining their consent, interviewees were invited by telephone or face-to-face to discuss whether the Lean implementation strategies identified from the literature existed in actual PC projects and could potentially affect the performance. Each interview lasted 1–2 h to confirm the reliability of the identified strategies. The interviewees also proposed additional strategies and described them in detail based on their own experiences. The opinions of different interviewees had the same weight. When disagreements among interviewees existed, these interviewees were contacted for further discussion. After three rounds of discussion, the interviewees reached an agreement for all questions. Ultimately, a list of 17 Lean implementation strategies could be generated after in-depth interviews, as shown in Table 2.

Table 2. Final Lean implementation strategies.

No.	Lean Implementation Strategies	Sources
S1	Establish a top-level plan and leadership team	[50]
S2	Develop an efficient decision-making organizational structure	[51,52]
S3	Implement a comprehensive performance evaluation and incentive mechanism	[11,19]
S4	Focus on customer needs and value	[53]
S5	Establish a comprehensive resource management system	[54,55]
S6	Enhance internal communication and collaboration within the enterprise	[56]
S7	Strengthen external communication and collaboration with the enterprise	[56]
S8	Develop a comprehensive risk management system	[57]
S9	Accurately formulate project implementation and scheduling plans	[58]
S10	Select appropriate Lean and information tools and technologies	[59]
S11	Strengthen process management and continuously optimize project plans and workflows	[60,61]
S12	Establish a standardized structural system and operational activities	[46]
S13	Develop a comprehensive system of standards, rules, and regulations	[62]
S14	Foster a lean and intelligent culture and employee awareness	[63]
S15	Emphasize employee knowledge acquisition and skills training	[64]
S16	Utilize external consulting firms and academic institutions for assistance	[50]
S17	Establish a continuous improvement mechanism and culture	[11,65]

3.2. The Network-Based ISM-MICMAC Model

A network-based ISM-MICMAC model integrating ISM, MICMAC, and complex networks is constructed. In the model, ISM-MICMAC aims to identify the strategies' structural relationships and roles, while TSW and SDW aim to evaluate strategies' importance through considering structural and mutual impact.

3.2.1. Structural Model Part: ISM-MICMAC for Lean Implementation Strategies

1. The ISM model of Lean implementation strategies in PC

ISM is a model that formulates a complex system into a visualized hierarchical structure and helps to understand the direct and indirect relationships among the strategies [66]. The steps for the ISM model are discussed below [3,10,45]:

Step 1: Lean implementation strategies are identified and listed through the extensive review of literature and experts' opinions.

Step 2: A contextual relationship among the identified strategies is developed to examine as to which pairs of Lean implementation strategies should be checked.

Step 3: A structural self-interaction matrix (SSIM) is developed that indicates pairwise relationships among strategies of the system.

In this step, the direct relationships among strategies can be evaluated from four aspects: W, X, Y, and Z, which are indicated as follows:

- W indicates that strategy *i* has a direct impact on strategy *j*, but the reverse is not true.
- X indicates that strategy *j* has a direct impact on strategy *i*, but the reverse is not true.
- Y indicates that there is a direct interaction between strategy *i* and strategy *j*.
- Z indicates that there is no direct interaction between strategy *i* and strategy *j*.

Step 4: A reachability matrix (RM) is constructed from the SSIM by replacing each cell entry of the SSIM by 1 and 0, and the matrix is checked for transitivity. The transitivity of the contextual relation is a basic assumption made in the ISM. It states if a strategy U is related to strategy V and strategy V is related to strategy W, then U is necessarily related to W. Thus, a final RM is developed.

Step 5: The final RM developed in Step 4 is categorized into different levels.

Step 6: A directed graph or digraph is drawn based on the contextual relationships given above in the reachability matrix, and then the transitive links are removed from the digraph.

Step 7: By substituting variable nodes with relationship statements, an ISM model is generated from the resultant digraph.

Step 8: The ISM model of Lean implementation strategies generated in Step 7 is reviewed to find out that any conceptual inconsistency and necessary modifications are considered through experts' opinions.

2. The MICMAC analysis for Lean implementation strategies in PC

MICMAC analysis complements the ISM by exploring constraints that usually are embedded within the ISM network [37]. In this analysis, the objective of MICMAC analysis is to identify the key strategies that drive the ISM model based on their driving power and dependence power [33]. The driving power and the dependence power of each strategy in MICMAC are obtained by summing the entries of possibilities of interactions in its row and column of the final reachability matrix of ISM. Seventeen Lean implementation strategies can be further classified into four categories based on the value of the driving power and the dependence: autonomous strategies (AUSs), dependent strategies (DESs), linkage strategies (LISs), and driving strategies (DRSs), which reflect their various roles and impacts for implementing Lean [33].

AUSs have minimal driving influence and dependency on other elements in the ISM network, resulting in a relatively small impact on achieving the network's objectives, making them of secondary consideration and focus [33]. DESs exhibit high dependency and relatively weak driving power, typically positioned at the upper levels of the ISM, which have a direct impact on the objectives and require close monitoring to assess the effectiveness of the lower-level strategies [38]. LISs possess high intensity in both driving power and dependency, typically located in the middle of the ISM, acting as a critical link between upper and lower levels. It plays a key role in achieving objectives and therefore requires focused attention and management [35]. DRSs have strong driving power and weak dependency, typically located at the lower levels of the ISM, serving as the foundation for the implementation of other strategies, resulting in them being the most critical strategies in the ISM and requiring priority attention and assurance [67].

3.2.2. Importance Evaluation Model Part: TSW and SDW of Lean Implementation Strategies in PC

To enhance the precision in assessing the importance of Lean implementation strategies, this paper integrates the influence of both the topological features of complex networks and the hierarchical structure of the ISM model on strategy importance [45]. By calculating the TSW and SDW, this paper computes the comprehensive weights of each Lean strategy to evaluate its relative importance. The steps for the TSW and SDW models are discussed below, according to Congliang et al. [68], Huang et al. [69], Yu et al. [70], Chen et al. [43], and Liu and Xu [45].

1. Importance evaluation model of Lean implementation strategies based on TSW

Step 1: Degree calculation of each node in the ISM network of Lean implementation strategies

In the ISM network of Lean implementation strategies, the degree of the node S_i set as D_{Si} refers to the number of nodes that have a direct impact relationship with it. Due to the directional influence relationship between various strategies, they may have an impact on other ones and may also be influenced. Among them, the number of edges pointing from S_i to other strategies is the output of S_i, set as ${D_{Si}}^{out}$. The number of edges pointing from other strategies to S_i is the in degree of S_i, set as ${D_{Si}}^{into}$. The calculation formula for the degree D_{Si} of S_i is shown in Equation (1) [43].

$$D_{Si} = \sum_{j=1}^{n} (a_{ij} + a_{ji}) - b = \sum_{j=1}^{17} (a_{ij} + a_{ji}) - b \tag{1}$$

where n is the number of Lean implementation strategies; S_i and S_j are two strategy nodes in the Lean strategy network; a_{ij} is the value between S_i and S_j in the AM illustrated in Appendix B; and b is the number of other strategies corresponding to strategy S_i, where both the row and column strategies are set to "1".

Step 2: Average degree calculation in the ISM network of Lean implementation strategies

The average degree (AD) of the ISM network is the average degree of all strategy nodes in the network, calculated using the formula shown in Equation (2) [43].

$$AD = \sum_{i=1}^{n} D_{si}/n = \sum_{i=1}^{17} D_{si}/17 \tag{2}$$

where n is the number of Lean implementation strategies and D_{Si} is the degree of S_i.

Step 3: Calculation of strategy node distance in the ISM network of Lean implementation strategies

In the ISM network of Lean implementation strategies, the distance between two strategy nodes S_i and S_j is defined as the minimum number of edges involved from S_i to S_j along the direction of the transmission relationship, denoted as d_{SiSj}. The calculation formula is presented as Equation (3) [43]. If there is no direct or indirect relationship between two strategy nodes S_i and S_j, their distance is infinity (∞).

$$d_{S_iS_j} = \min_{i,j}(l_{S_iS_j}) \tag{3}$$

where l_{SiSj} represents the length of all paths between strategy node S_i and node S_j, that is, the number of edges.

Step 4: Efficiency calculation of strategy nodes in the ISM network of Lean implementation strategies

In the ISM network of Lean implementation strategies, the efficiency of a strategy node S_i, denoted as E_{Si}, is a metric reflecting the speed at which the strategy influences other strategies. It is inversely proportional to the node distance d_{SiSj}, with the calculation formula provided in Equation (4) [43].

$$E_{S_i} = \frac{1}{n-1} \sum_{j=1, j\neq i}^{n} \frac{1}{d_{S_iS_j}} = \frac{1}{16} \sum_{j=1, j\neq i}^{17} \frac{1}{d_{S_iS_j}} \tag{4}$$

where n is the number of Lean implementation strategies and d_{SiSj} is the distance between strategy nodes S_i and S_j.

Step 5: Construction of a node importance contribution matrix in the ISM network of Lean implementation strategies

Through Steps 1 to 4, the basic topological structure parameters of the ISM network of Lean implementation strategies, including node degree, network degree, node distance, and node efficiency, have been calculated. Further consideration is given to the interrelationships between strategies, particularly the impact on the importance of adjacent strategies. This mutual influence of importance between strategies can be measured through the Importance Contribution Value (*ICV*) of strategy nodes. *ICV* can be calculated according to Equation (5), representing the importance contribution of the Lean strategy S_i to its adjacent strategies, denoted as CV_{Si} [43,69,70].

$$ICV_{S_i} = D_{S_i} / AD^2 \tag{5}$$

In Equation (5), D_{Si} denotes the degree of strategy node S_i, and AD is the average degree of the ISM network of Lean implementation strategies.

Based on the *ICV* of strategy nodes, an importance contribution matrix (*ICM*) for the entire ISM network of Lean implementation strategies can be constructed. Strategy nodes only contribute importance to adjacent nodes that have a direct impact on them, and the constructed *ICM* is shown in Equation (6) [43,69,70].

$$ICM = \begin{bmatrix} 1 & a_{12}ICV_{S_2} & \cdots & a_{1n}ICV_{S_n} \\ a_{21}ICV_{S_1} & 1 & \cdots & a_{2n}ICV_{S_n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}ICV_{S_1} & a_{n2}ICV_{S_2} & \cdots & 1 \end{bmatrix} \tag{6}$$

In Equation (6), a_{ij} is an element in the adjacency matrix of the ISM network of Lean implementation strategies, with a value of "1" or "0". ICV_{Si} is the node importance contribution matrix of S_i.

Step 6: Construction of a node importance evaluation matrix in the ISM network of Lean implementation strategies

Based on *ICM* in Step 5, to further consider the impact of efficiency between strategy nodes, the *ICV* and efficiency values of strategy nodes are integrated to define the Importance Evaluation Value (*IEV*) of strategy nodes, as shown in Formula (7) [43,69,70].

$$IEV_{S_i} = E_{S_i} * ICV_{S_i} \tag{7}$$

In Formula (7), E_{Si} represents the efficiency of strategy S_i; ICV_{Si} represents the contribution value of the importance of strategy S_i.

Based on this, it is feasible to construct an importance evaluation matrix (*IEM*) for the ISM network of Lean implementation strategies. The computational formula of IEM is illustrated in Equation (8) [43,69,70].

$$IEM = \begin{bmatrix} 1 & a_{12}E_{S_2}ICV_{S_2} & \cdots & a_{1n}E_{S_n}ICV_{S_n} \\ a_{21}E_{S_1}ICV_{S_1} & 1 & \cdots & a_{2n}E_{S_n}ICV_{S_n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}E_{S_n}ICV_{S_1} & a_{n2}E_{S_2}ICV_{S_2} & \cdots & 1 \end{bmatrix} \tag{8}$$

Where a_{ij} is an element in the adjacency matrix of the ISM network of Lean implementation strategies, with its value of "1" or "0"; E_{Si} is the efficiency of strategy S_i; and ICV_{Si} is the contribution value of the importance of S_i.

Step 7: Calculating the importance weight of each strategy in the ISM network of Lean implementation strategies

Based on *IEM*, by comprehensively considering the efficiency E_{Si} of the strategy node S_i and the importance evaluation value IEV_{Sj} of the strategy S_j affected by it, its importance weight w_{si} in the network can be calculated, shown as in Equation (9) [43,69,70].

$$w_{S_i} = E_{S_i} \sum_{j=1, j \neq i}^{n} IEV_{S_j} \tag{9}$$

2. Importance evaluation model of Lean implementation strategies based on SDW

Based on calculating the importance weight values of Lean implementation strategies based on TSW, it is necessary to further comprehensively consider the impact of the structural hierarchy of strategy nodes in the ISM network on their own importance. Thereby, this paper further uses a strategy node importance evaluation method that considers the out degree, in degree, and ISM model hierarchy of strategy nodes to determine their SDW. The calculation process based on SDW mainly consists of three steps, namely calculating the level weights of the ISM model, determining the impact coefficients of the out degree and in degree of the strategy nodes, and calculating the structured weights of the strategy nodes.

Step 1: Level weight calculation of the ISM network of Lean implementation strategies

Based on the ISM model and MICMAC analysis, Lean implementation strategies at different levels have different roles and importance in the successful implementation of Lean in PC. To this end, the network level weight (*LW*) is used to represent the importance level of each level in the ISM model, and the specific calculation formula is shown in Equation (10) [45].

$$LW_{L_i} = 1/i \Big/ \sum_{i=1}^{N}(1/i) \tag{10}$$

In Formula (10), i is the structural hierarchy value of the ISM model, i = 1, 2, 3. . ., N.

Step 2: Determining the impact coefficients of the out degree and in degree of the strategy nodes in the ISM network

In analyzing the importance of strategy nodes based on the ISM model, it is not only necessary to consider the network level located in the strategy node but also to consider the level of other strategy nodes that have a direct impact on strategies. As mentioned above, strategies affect or are influenced by other strategies, corresponding to the out-degree nodes and in-degree nodes in the ISM model, whose importance influence coefficients can be expressed as O and I, respectively, with $O < I$ and $O + I = 1$.

Step 3: Structured weight calculation of implementation strategy nodes in the ISM network

By calculating the level weights of the ISM network and impact coefficients of the out degree and in degree of the strategy nodes, the structural weight (*SW*) of each strategy node can be further calculated. The calculation formula is shown in Equation (11) [45]

$$SW_{S_i} = LW_{S_i}(I\sum_k LW_{Sk\to Si}N_{Sk\to Si} + O\sum_j LW_{S_i\to S_j}N_{S_i\to S_j}) \tag{11}$$

In Equation (11), LW_{Si} represents the level weight of the ISM model where the strategy node S_i is located; S_j and S_k represent the strategy nodes S_i points to and is directed to, respectively; and $LW_{Si\to Sj}$, $N_{Si\to Sj}$, $LW_{Sk\to Si}$, and $N_{Sk\to Si}$, respectively, represent the level weights and their own numbers of strategy nodes S_j and S_k in the ISM model.

3. Comprehensive importance evaluation of Lean implementation strategies in PC

Based on the importance weights based-TSW w_{si} and based-SDW SW_{Si}, it is necessary to integrate the w_{si} and SW_{Si} to scientifically evaluate the importance of Lean implementation strategies. The comprehensive weight (*CW*) by multiplying the w_{si} with SW_{Si} is shown in Equation (12) [45].

$$CW_{\mathrm{S_i}} = w_{S_i} * SW_{S_i} \tag{12}$$

3.3. Data Collection

The interrelationships among strategies in the ISM model are determined through experts' evaluation, which is also the data source of MICMAC analysis and importance calculation. In other words, the interrelationships are initially identified through literature review. Then, 30 experts from Table 1 are invited to evaluate the importance of each mutual relationship between strategies using a five-point Likert scale and applying the principle of "the minority yielding to the majority" [3]. Specifically, if the number of experts who evaluate the relationship as "4" and "5" exceeds 15, then the relationship between the strategies is considered to exist. Thus, all mutual relationships among strategies can be constructed to establish SSIM and further calculate the processes of the model.

3.4. Data Analysis and Model Caculation

Finally, the structural hierarchy, the roles and importance of Lean implementation strategies in PC, and corresponding planning were determined, and effective measures for enhancing project performance for stakeholders were identified by emphasizing the crucial roles of important Lean implementation strategies.

4. Results and Discussion

4.1. Structural Analysis of Lean Implementation Strategies-Based ISM

1. Constructing the ISM model of Lean implementation strategies in PC

Step 1: Establishing the structural relationships among Lean implementation strategies and SSIM

The interrelationships among strategies are determined through a literature review and 30 experts' evaluations, which are described in Section 3.2.1. Then, the final SSIM is constructed, shown as in Appendix A.

Step 2: Establishing AM of Lean implementation strategies in PC

The structural relationships of W, X, Y, and Z in SSIM are converted into a binary matrix represented by "0" or "1" to construct the AM of Lean implementation strategies, as shown in Appendix B.

Step 4: Constructing RM of Lean implementation strategies in PC

The *RM* is obtained through Boolean operations based on *AM*. Specifically, the *AM* is added to the identity matrix I to obtain the matrix ($AM + I$). Boolean operations are then performed on it until the matrix no longer changes, resulting in *RM*. The formula is shown as follows, where k represents the number of iterations of the matrix.

$$(AM + I)^1 \neq (AM + I)^2 \neq (AM + I)^3 \neq \ldots \neq (AM + I)^{k-1} = (AM + I)^k = RM \quad (13)$$

It was revealed that when $k = 7$, $(AM + I)^6 = (AM + I)^7$, RM can be obtained as $RM = (AM + I)^6 = (AM + I)^7$, which is shown in Appendix C.

Step 5: Level division of Lean implementation strategies

The 17 Lean implementation strategies can be further divided into different levels based on the RM, according to the steps of hierarchical division in (24; 16). The results of level division are as follows: $L_1 = [S_8]$, $L_2 = [S_4, S_5, S_9, S_{11}]$, $L_3 = [S_6, S_7]$, $L_4 = [S_{17}]$, $L_5 = [S_{10}, S_{12}, S_{16}]$, $L_6 = [S_2, S_3, S_{13}]$, $L_7 = [S_{14}, S_{15}]$, $L_8 = [S_1]$.

Step 6: Constructing the ISM model of the Lean implementation strategies in PC

A preliminary diagram illustrating the interrelationships of 17 strategies based on AM is initially created, as shown in Figure 2. Additionally, this figure demonstrates that the complex relationships between strategies form a complex network. This provides a starting point for exploring the mutual influence and importance of strategies using complex network theory.

The ISM model is accordingly constructed, clearly reflecting the interaction and hierarchy of Lean implementation strategies, which is shown in Figure 3.

As in Figure 3, the ISM model for Lean implementation strategies is a multi-level progressive network system with an eight-level hierarchical structure. The Lean implementation strategies positioned at different structural levels are closely connected and mutually influential, highlighting the differentiated roles of these strategies in the successful Lean implementation. The strategies located at the lower levels of the ISM model directly or indirectly impact the upper-level strategies while simultaneously supporting and promoting the successful LC implementation.

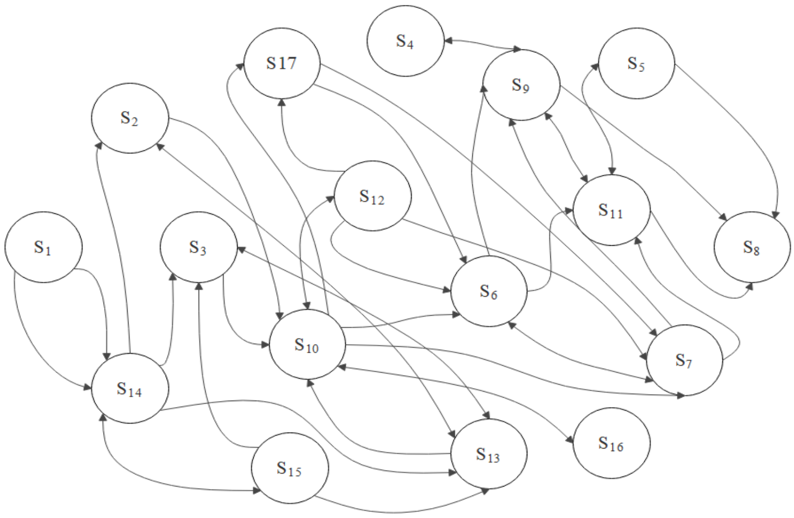

Figure 2. Structural relationship network among 17 Lean implementation strategies.

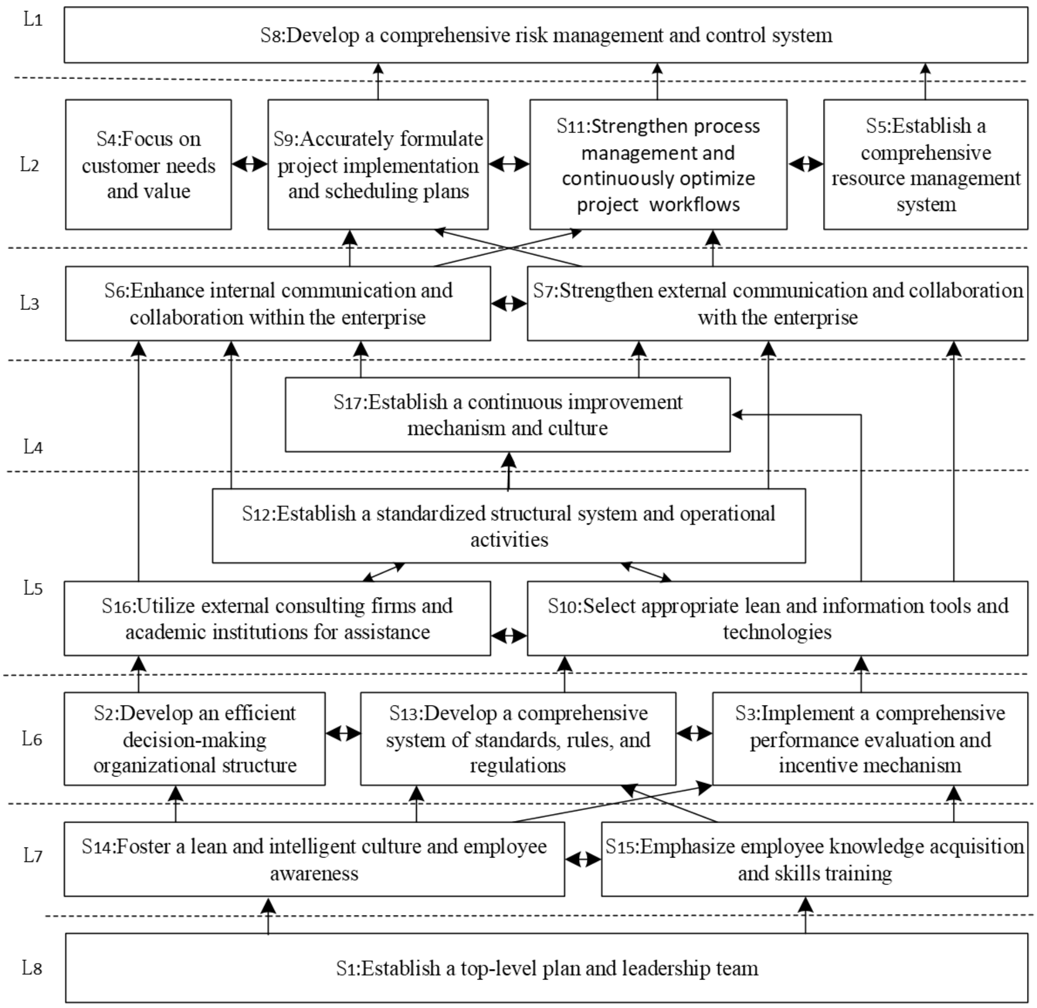

Figure 3. The ISM model of Lean implementation strategies in PC.

2. MICMAC analysis of the ISM model of Lean implementation strategies in PC

As aforementioned in Section 3.2.1, MICMAC is used to analyze the role of strategies in the ISM network. The 17 Lean implementation strategies can be classified into four categories: AUSs, DESs, LISs, and DRSs, based on the DRP and DEP values [33]. The DRP and DEP values can be calculated, as shown in Appendix D. The results can be plotted in quadrants based on the DRP as the horizontal axis and DEP as the vertical axis, as shown in Figure 4.

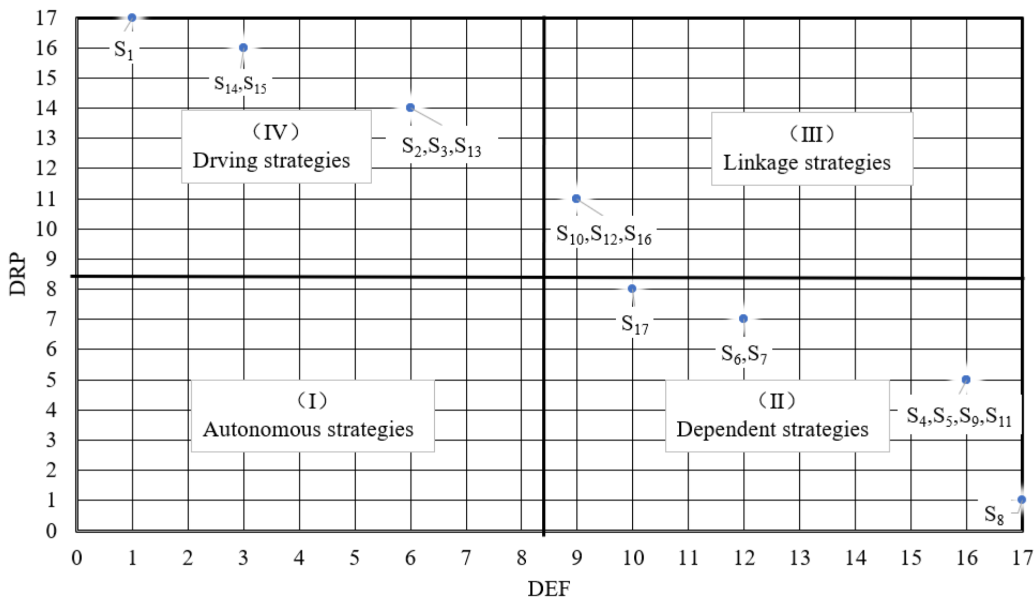

Figure 4. Category distribution of the 17 Lean implementation strategies based on MICMAC.

In Figure 4, there are no Lean implementation strategies distributed in the bottom-left quadrant (Quadrant I) of AUSs, which indicates that they are not independent of each other, rather having complex interrelationships and mutual influences. S_{17}, S_6, S_7, S_4, S_5, S_9, S_{11}, and S_8 are in the bottom-right quadrant (Quadrant II) as DESs, which are generally positioned at the upper levels of the ISM model and have a strong dependency on the lower-level strategies. S_{10}, S_{12}, and S_{16} are in the top-right quadrant (Quadrant III) as LISs, which are generally positioned in the middle levels of the ISM model, characterized by importance on other strategies and the successful Lean implementation. S_1, S_{14}, S_{15}, S_2, S_3, and S_{13} are in the bottom-right quadrant (Quadrant IV) as DRSs, which are generally positioned at the lower levels of the ISM model and have a significant influence on other strategies.

4.2. Importance Analysis

1. Importance evaluation of Lean implementation strategies based on TSW

The weights of Lean implementation strategies are calculated based on network topology to evaluate the importance of each strategy. The evaluation process primarily involves analyzing network characteristics such as strategy node degree D_{Si}, average degree AD, node distance d_{SiSj}, and node efficiency E_{Si}. The ICM and IEM are constructed to determine the weights of the strategy nodes, according to Equations (1)–(9).

Step 1: Degree of strategy nodes in the ISM network

The degree of the 17 Lean strategy nodes within the ISM network is calculated by Equation (1). The calculation results are detailed in Table 3.

Table 3. Degree of the 17 Lean implementation strategies.

Strategy	Node	Degree of Node	Strategy	Node	Degree of Node
S_1	D_{S1}	2	S_{10}	D_{S10}	8
S_2	D_{S2}	3	S_{11}	D_{S11}	5
S_3	D_{S3}	3	S_{12}	D_{S12}	4
S_4	D_{S4}	1	S_{13}	D_{S13}	5
S_5	D_{S5}	2	S_{14}	D_{S14}	5
S_6	D_{S6}	6	S_{15}	D_{S15}	4
S_7	D_{S7}	6	S_{16}	D_{S16}	1
S_8	D_{S8}	3	S_{17}	D_{S17}	4
S_9	D_{S9}	5		—	

Step 2: Average degree of the ISM network of Lean implementation strategies

The AD of the Lean implementation strategies is calculated by Equation (2). The *AD* is *67/17 = 3.9*, which indicates each lean construction implementation strategy has an averagely direct influence on approximately four other strategies.

Step 3: Node distance of strategies in the ISM network

The node distance (*D*) between two strategies S_i and S_j (d_{SiSj}) is defined as the minimum number of edges involved from S_i to S_j along the direction of the transmission relationship. The *D* between 17 Lean implementation strategies is determined by Equation (3), shown in Appendix E.

Step 4: Efficiency of strategy nodes in the ISM network

The efficiency (*E*) of strategy nodes is a metric reflecting the speed at which the strategy influences other strategies. The E of strategy nodes S_1–S_{17}, denoted as E_{S1}–E_{S17}, are calculated by Equation (4) and are provided in detail in Table 4.

Table 4. E of the 17 Lean implementation strategies.

Strategy	Node	E of Node	Strategy	Node	E of Node
S_1	E_{S1}	0.374	S_{10}	E_{S10}	0.438
S_2	E_{S2}	0.401	S_{11}	E_{S11}	0.219
S_3	E_{S3}	0.401	S_{12}	E_{S12}	0.375
S_4	E_{S4}	0.104	S_{13}	E_{S13}	0.432
S_5	E_{S5}	0.177	S_{14}	E_{S14}	0.454
S_6	E_{S6}	0.281	S_{15}	E_{S15}	0.423
S_7	E_{S7}	0.281	S_{16}	E_{S16}	0.276
S_8	E_{S8}	0.000	S_{17}	E_{S17}	0.250
S_9	E_{S9}	0.219		—	

Step 5: Node importance contribution matrix for the ISM network

The influencing interrelationships between strategies can be measured through the *ICV* of strategy nodes. The *ICV* of 17 Lean implementation strategies can be calculated by Equation (5). Then, the *ICM* for the entire ISM network can be further constructed according to Equation (6), which is shown in detail in Appendix F.

Step 6: Node importance evaluation matrix for the ISM network

The *ICV* and E of 17 Lean implementation strategy nodes are integrated to define *IEV*, which can be calculated by Equation (7). Then, the IEM of the 17 strategies can be further constructed according to Equation (8), which is shown in detail in Appendix G.

Step 7: The Topological Structure Weight of strategy nodes in the ISM network

The Topological Structure Weight (w) of the 17 Lean implementation strategies can be finally determined by Equation (9), by considering the E_{Si} and IEV_{Sj} of S_j affected by it. The results are shown in Table 5.

Table 5. The w of 17 Lean implementation strategies in PC.

Strategy	Code of Weight	Value of Weight	Strategy	Code of Weight	Value of Weight
S_1	w_{S1}	0.097	S_{10}	w_{S10}	0.177
S_2	w_{S2}	0.149	S_{11}	w_{S11}	0.021
S_3	w_{S3}	0.149	S_{12}	w_{S12}	0.194
S_4	w_{S4}	0.007	S_{13}	w_{S13}	0.168
S_5	w_{S5}	0.013	S_{14}	w_{S14}	0.187
S_6	w_{S6}	0.072	S_{15}	w_{S15}	0.157
S_7	w_{S7}	0.072	S_{16}	w_{S16}	0.064
S_8	w_{S8}	0.000	S_{17}	w_{S17}	0.056
S_9	w_{S9}	0.017		—	

2. Importance evaluation of Lean implementation strategies based on SDW

The structural weight (SW)-based ISM network can be calculated by Equations (10) and (11). The SWs of 17 Lean implementation strategies are shown in Table 6.

Table 6. The SW of 17 Lean implementation strategies in PC.

S_i	L_i	LW_{Si}	S_k	S_j	$I\sum_k LW_{Sk\to Si}N_{Sk\to Si}$	$O\sum_j LW_{S_i\to S_j}N_{S_i\to S_j}$	SW_{Si}
S_1	L_8	0.046	0	S_{14}, S_{15}	0.0000	0.0530	0.0024
S_2	L_6	0.061	S_{14}, S_{13}	S_{13}, S_{10}	0.1710	0.0675	0.0145
S_3	L_6	0.061	S_{14}, S_{13}, S_{15}	S_{13}, S_{10}	0.3758	0.0675	0.0270
S_4	L_2	0.184	S_9	S_9	0.1380	0.0460	0.0339
S_5	L_2	0.184	S_{11}	S_{11}, S_8	0.1380	0.2760	0.0762
S_6	L_3	0.123	S_{10}, S_{12}, S_{17}, S_7	S_7, S_{11}, S_9	1.0890	0.3683	0.1792
S_7	L_3	0.123	S_6, S_{17}, S_{10}, S_{12}	S_6, S_{11}, S_9	1.0890	0.3683	0.1792
S_8	L_1	0.368	S_9, S_5, S_{11}	0	1.2420	0.000	0.4570
S_9	L_2	0.184	S_4, S_6, S_7, S_{11}	S_4, S_{11}, S_8	1.8420	0.5520	0.4405
S_{10}	L_5	0.074	S_{16}, S_2, S_{13}, S_3, S_{12}	S_{16}, S_{12}, S_6, S_{17}, S_7	1.2413	0.6075	0.1368
S_{11}	L_2	0.184	S_9, S_6, S_7, S_5	S_9, S_5, S_8	1.8420	0.5520	0.4405
S_{12}	L_5	0.074	S_{10}	S_{10}, S_6, S_7, S_{17}	0.0555	0.4120	0.0346
S_{13}	L_6	0.061	S_2, S_{14}, S_{15}, S_3	S_2, S_3, S_{10}	0.6840	0.1470	0.0507
S_{14}	L_7	0.053	S_1, S_{15}	S_{15}, S_2, S_{13}, S_3	0.1485	0.2360	0.0204
S_{15}	L_7	0.053	S_1, S_{14}	S_{14}, S_{13}, S_3	0.1485	0.1313	0.0148
S_{16}	L_5	0.074	S_{10}	S_{10}	0.0555	0.0185	0.0055
S_{17}	L_4	0.092	S_{10}, S_{12}	S_6, S_7	0.2220	0.1230	0.0317

3. Comprehensive importance weights of Lean implementation strategies in PC

Based on the importance weights of w and SW, it is integrating them to obtain CW to more scientifically and comprehensively evaluate the importance of Lean implementation strategies. CWs of 17 Lean implementation strategies can be calculated by Equation (12) and are shown in Table 7.

4.3. Structural and Importance Analysis of Lean Implementation Strategies in PC

The comprehensive structural and importance analyses of 17 Lean implementation strategies in PC are described in Table 8.

As shown in Table 8, Lean implementation strategies positioned at higher levels of ISM correspond to DESs identified through MICMAC analysis. These strategies have the most direct impact on successful Lean implementation. They are supported by lower-level strategies and are crucial for monitoring and evaluating the effectiveness of other strategies. For example, the Lean strategy S_8: Develop a comprehensive risk management system exhibits the strongest dependency and weakest driving force, which aligns with its position at the top level (L_1) of the ISM model, relying on the implementation of lower-level strategies. Lean implementation strategies positioned at intermediate levels of the ISM correspond to LISs identified through MICMAC analysis. These strategies play a pivotal role in connecting the lower and upper levels, meaning they must inherit the outcomes of lower-level strategies while also providing support for the implementation of upper-level strategies. Therefore, these strategies are the most critical and require the greatest attention.

Table 7. The CW of 17 Lean implementation strategies in PC.

S_i	w_{Si}	SW_{Si}	$*CW_{Si}$	Rank	Ordering Rank	S_i
S_1	0.097	0.0024	0.000236486	16	1	S_{10}
S_2	0.149	0.0145	0.002167727	11	2	S_6
S_3	0.149	0.0270	0.004028699	8	3	S_7
S_4	0.007	0.0339	0.000236992	15	4	S_{11}
S_5	0.013	0.0762	0.000990288	13	5	S_{13}
S_6	0.072	0.1792	0.012905406	2	6	S_9
S_7	0.072	0.1792	0.012905406	3	7	S_{12}
S_8	0.000	0.4570	0.00000000	17	8	S_3
S_9	0.017	0.4405	0.007488432	6	9	S_{14}
S_{10}	0.177	0.1368	0.024214928	1	10	S_{15}
S_{11}	0.021	0.4405	0.009250416	4	11	S_2
S_{12}	0.194	0.0346	0.006711430	7	12	S_{17}
S_{13}	0.168	0.0507	0.008516088	5	13	S_5
S_{14}	0.187	0.0204	0.003810780	9	14	S_{16}
S_{15}	0.157	0.0148	0.002327800	10	15	S_4
S_{16}	0.064	0.0055	0.000350464	14	16	S_1
S_{17}	0.056	0.0317	0.001777440	12	17	S_8

Note: "*" indicates that more decimal places have been retained to better distinguish the strategy weights and rankings, due to the similarity in the weight values of some Lean construction strategies.

Table 8. Comprehensive structural and importance analyses of 17 Lean implementation strategies.

S_i	Importance	ISM	ISM-Based Role Analysis	MICMAC	MICMAC-Based Role Analysis
S_{10}	1	L_5	Positioned in the middle level, it belongs to the technical aspect, supporting upper-level strategies through technical implementation based on lower-level strategies	Linkage Strategy	Has strong driving and dependency relationships with other strategies, making it critical and requiring close management
S_6	2	L_3	Located at the third-highest level, it has a direct impact on LC implementation but also serves as a key link that transmits the effects of lower-level strategies and supports upper-level	Dependent Strategy	Has high dependency on other strategies but also possesses some driving force, requiring monitoring and some attention
S_7	3	L_3	Located at the third-highest level, it has a direct impact on the successful implementation of LC but also serves as a key link that transmits the effects of lower-level strategies and supports upper-level strategies	Dependent Strategy	Has high dependency on other strategies but also possesses some driving force, requiring monitoring and some attention
S_{11}	4	L_2	Located at the second-highest level, it has a more direct impact on the successful implementation of LC but also serves as a key link that monitors the effects of lower-level strategies and supports the implementation of upper-level strategies	Dependent Strategy	Has the second-highest dependency on other strategies and a relatively weaker driving force, requiring monitoring and some attention to assess the effectiveness of lower-level strategies
S_{13}	5	L_6	Located at the third-lowest level, it provides relatively fundamental support for LC implementation	Driving Strategy	Has the third-strongest driving force and weaker dependency on other strategies, forming the foundation for successful LC and requiring early attention

Table 8. *Cont.*

S_i	Importance	ISM	ISM-Based Role Analysis	MICMAC	MICMAC-Based Role Analysis
S_9	6	L_2	Located at the second-highest level, it has a more direct impact on the successful implementation of LC but also serves as a key link that monitors the effects of lower-level strategies and supports upper-level strategies	Dependent Strategy	Has the second-highest dependency on other strategies and a relatively weaker driving force, requiring monitoring and some attention to assess the effectiveness of lower-level strategies
S_{12}	7	L_5	Positioned in the middle level, it belongs to the technical aspect of LC implementation, supporting upper-level strategies through technical implementation based on lower-level	Linkage Strategy	Has strong driving and dependency relationships with other strategies, making it critical and requiring close management
S_3	8	L_6	Located at the third-lowest level, it provides relatively fundamental support for LC implementation	Driving Strategy	Has the third-strongest driving force and weaker dependency on other strategies, forming the foundation for successful LC and requiring early attention
S_{14}	9	L_7	Located at the second-lowest level, it provides important foundational support for LC implementation and is necessary for early-stage implementation	Driving Strategy	Has the second-strongest driving force and weaker dependency on other strategies, forming the foundation for successful Lean and requiring early attention
S_{15}	10	L_7	Located at the second-lowest level, it provides important foundational support for LC implementation and is necessary for early-stage implementation	Driving Strategy	Has the second-strongest driving force and weaker dependency on other strategies, forming the foundation for successful Lean and requiring early attention
S_2	11	L_6	Located at the third-lowest level, it provides relatively fundamental support for LC implementation	Driving Strategy	Has the third-strongest driving force and weaker dependency on other strategies, forming the foundation for successful LC and requiring early attention
S_{17}	12	L_4	Positioned in the middle level, it belongs to the technical aspect of LC implementation, supporting upper-level strategies through technical implementation based on lower-level	Dependent Strategy	Has high dependency on other strategies but also possesses some driving force, requiring monitoring and some attention
S_5	13	L_2	Located at the second-highest level, it has a more direct impact on the successful implementation of LC but also serves as a key link that monitors the effects of lower-level strategies and supports upper-level strategies	Dependent Strategy	Has the second-highest dependency on other strategies and a relatively weaker driving force, requiring monitoring and some attention to assess the effectiveness of lower-level strategies
S_{16}	14	L_5	Positioned in the middle level, it belongs to the technical aspect of LC implementation, supporting upper-level strategies through technical implementation based on lower-level strategies	Linkage Strategy	Has strong driving and dependency relationships with other strategies, making it critical and requiring close management for the successful implementation of LC

Table 8. *Cont.*

S_i	Importance	ISM	ISM-Based Role Analysis	MICMAC	MICMAC-Based Role Analysis
S_4	15	L_2	Located at the second-highest level, it has a more direct impact on the successful implementation of LC but also serves as a key link that monitors the effects of lower-level strategies and supports upper-level strategies	Dependent Strategy	Has the second-highest dependency on other strategies and a relatively weaker driving force, requiring monitoring and some attention to assess the effectiveness of lower-level strategies
S_1	16	L_8	Located at the lowest level, it is the most fundamental Lean strategy and should be prioritized	Driving Strategy	Has the strongest driving force and weakest dependency on other strategies, forming the most basic part of LC implementation and requiring top priority
S_8	17	L_1	Located at the highest level, it has the most direct impact on the successful implementation of LC and requires the most focused monitoring	Dependent Strategy	Directly impacts LC implementation, has the highest dependency on other strategies, and is the weakest driving force, requiring focused monitoring to assess the effectiveness of other strategies

Additionally, it is important to note that when evaluating the importance of Lean implementation strategies using complex networks, the implementation sequence of strategies is overlooked. For instance, strategy S_{16}: Utilize external consulting firms and academic institutions for assistance ranks 14th, and strategy S_6: Enhance internal communication and collaboration within the stakeholders ranks 2nd. Moreover, S_6 needs to be implemented first in terms of importance. However, S_{16} serves as the foundation for implementing S_6. According to the sequence derived from ISM and MICMAC analysis, S_{16} should be prioritized for implementation.

Thereby, this demonstrates that the network-based ISM-MICMAC analysis of Lean implementation strategies is complementary. It not only clearly demonstrates the hierarchical order of priorities for the successful implementation of lean but also establishes the key strategies within each level. This provides a solid foundation for accurately defining and formulating the implementation planning for Lean.

4.4. The Planning of Lean Implementation in PC

Accordingly, a structured and clearly prioritized plan for the successful Lean implementation in PC can be developed through exploring the strategies' interrelationships, roles, and importance. As illustrated in Figure 5, Lean implementation strategies highlighted with a light blue background hold higher importance and require more attention at their respective levels. These highlighted key strategies are selected according to the rank of comprehensive weights from first to eighth. The implementation planning of Lean in PC can be divided into four levels: the foundation level (Level 1), the organizational level (Level 2), the technical level (Level 3), and the control level (Level 4).

Level 1 of the planning is mainly composed of strategies at lower levels of the ISM model, including S_1 in level L_8, and S_{14} and S_{15} in level L_7. These strategies are all "driving strategies", which support the implementation of other strategies. Level 2 of the planning consists of strategies at slightly lower levels of the ISM model, including S_2, S_3, and S_{13} in level L_6. Although these strategies are categorized as "driving strategies" in the MICMAC analysis, they are not classified as the foundation level, considering they have dependence on S_1 in L_8, and S_{14} and S_{15} in L_7. They are considered the organizational level due to the important support of organizational structure in Lean implementation. Level 3 of the planning is composed of strategies near the middle of the ISM, including S_{16}, S_{10}, and S_{12} in L_5, S_{17} in L_4, and S_6 and S_7 in L_3, which are key technical strategies for the Lean successful implementation. Among them, S_{16}, S_{10}, and S_{12} are "linkage strategies"; although S_{17}, S_6, and S_7 are "dependency strategies", they have relatively high driving forces, which are classified as the technical level. Level 4 of planning is composed of strategies at higher levels of ISM, including S_8 in L_1 and S_4, S_9, S_{11}, and S_5 in L_2. These strategies are all "dependency strategies" that directly impact the Lean successful implementation. Since the implementation of these strategies depends on the support of other strategies, their effectiveness serves as an indicator of the overall success of these related strategies and necessitates focused control.

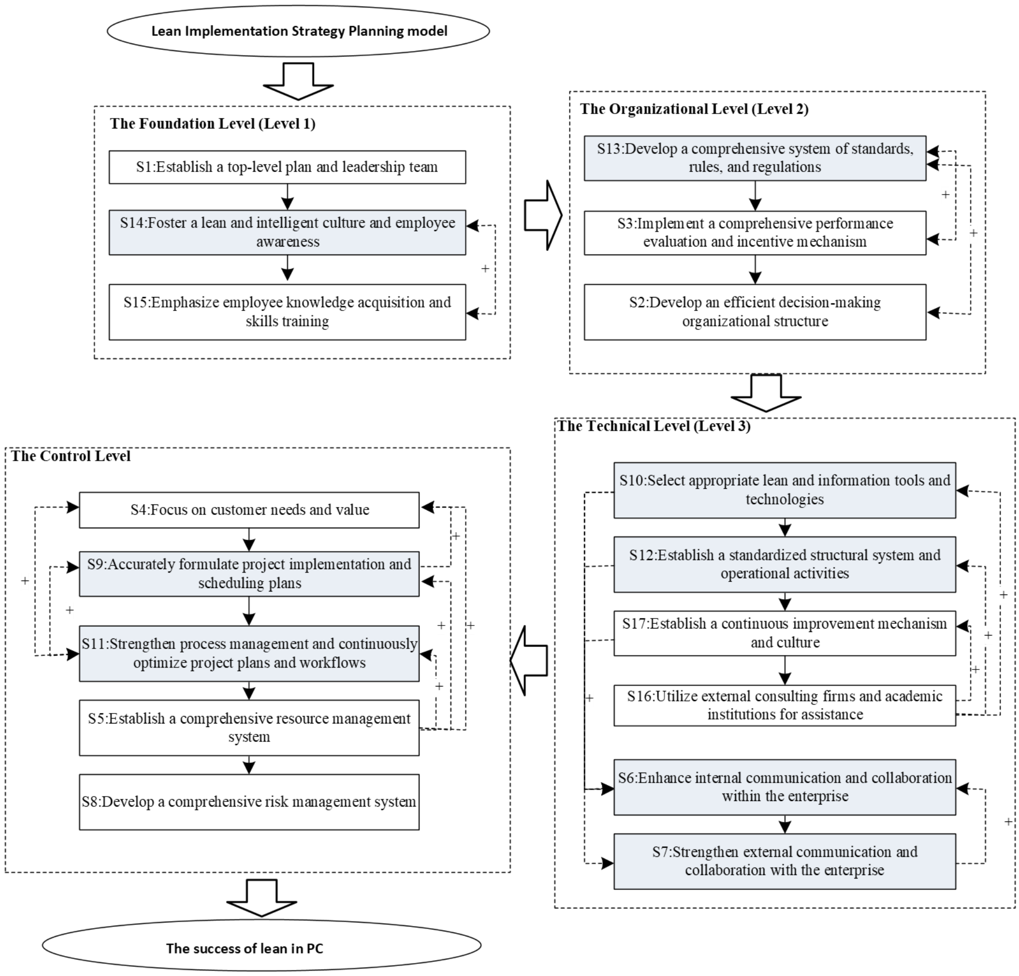

Figure 5. The planning of Lean implementation strategies.

4.5. Discussion

A network-based ISM-MICMAC model was utilized to explore the planning of Lean implementation strategies in the PC context. This model comprises two main parts: the structural model part and the importance analysis part. A total of 17 Lean implementation strategies for Chinese PC were analyzed, leading to four levels of planning of Lean implementation strategies.

The foundation-level strategies consist of Lean implementation strategies, S_1, at level L_8, and S_{14} and S_{15} at level L_7. The results indicate a top-level plan and leadership team (S_1) should be established to charge the overall Lean initiatives. This is essential because Lean involves a series of changes in projects' management and operational processes [50]. Moreover, this argument is supported by Netland et al. [71], who assert that Lean is a systemic project involving various aspects of man, machine, materials, method, and environment, requiring a top-level leadership group to mobilize resources for strategy implementation and process change. Additionally, fostering a lean and intelligent culture and raising employee awareness (S_{14}) is crucial, as organizations and employees may resist transitioning from traditional practices to Lean implementation [63]. Similarly, Santorella [72] emphasized that Lean tools alone are insufficient for successful Lean implementation, highlighting the critical role of Lean culture. Thereby, skills training and knowledge sharing (S_{15}) should be provided to employees to enhance employees' theoretical knowledge and practical experience in Lean [64]. However, the development of these skill sets remains limited [73].

The organizational-level strategies comprise Lean implementation strategies, S_2, S_3, and S_{13} at level L_6. The results indicate that successful Lean implementation requires a sound organizational structure, including standardized systems and incentives. This is particularly important as the Chinese construction industry and its stakeholders are in the early stage of transitioning from traditional construction to PC and have not yet developed an organizational structure suitable for this shift [52]. In this regard, Bajjou et al. [51] argued that Lean implementation necessitates organizational structure transformation, posing additional challenges for the construction industry and its stakeholders. Therefore, a comprehensive system of standards, rules, and regulations (S_{13}) needs to be constructed to support Lean transformation, which is also indicated by Demirkesen, S., and Bayhan, H.G. [74]. Secondly, a performance evaluation and incentive mechanism (S_3) should be developed to promote employee mindset transformation and motivate their participation in Lean implementation. The effectiveness of such mechanisms has been demonstrated in numerous project management studies [75–77]. Additionally, it is important to improve the decision-making efficiency and structure of the organization (S_2) to support the rapid allocation of resources during the Lean implementation [51,52].

The technical-level strategies include Lean implementation strategies S_{16}, S_{10}, and S_{12} at level L_5, S_{17} at level L_4, and S_6 and S_7 at level L_3. In fact, stakeholders in PC often lack Lean knowledge and experience, and internal and external operations are segmented, which are key factors hindering successful Lean [19]. To address this, selecting appropriate Lean tools and information technologies (S_{10}) is the most key strategy for successful Lean implementation [59]. This has been justified by Lermen et al. [78] and Deanese et al. [79]. Furthermore, the standardized system and operational processes (S_{12}) are also vital for Lean implementation [46]. Then, a continuous improvement mechanism and culture (S_{17}) should be established, as Lean is a long-term dynamic process that requires ongoing optimization of technologies and processes in response to changes in business and project environments [11,65]. In this process, external consulting firms and academic institutions (S_{16}) can provide valuable assistance in addressing challenges encountered during Lean implementation [50]. Additionally, internal and external communication and collaboration among stakeholders (S_6 and S_7), such as concurrent engineering and collaborative supply chains, need to be enhanced to further improve the effectiveness of Lean [56].

The control-level strategies include Lean implementation strategies S_8 at level L_1 and S_4, S_9, S_{11}, and S_5 at level L_2. Lean success is reflected in the performance of PC projects, which depends on meeting customer needs and values [53]. Thus, prioritizing customer needs and values (S_4) in terms of duration, cost, and quality is essential, as it directly affects project performance. Accurate project implementation and scheduling plans (S_9) are also crucial to ensuring these outcomes. However, various factors, such as environmental and technological changes, can disrupt PC processes [58]. Thereby, continuous optimization of project plans and processes (S_{11}) and a comprehensive resource management system (S_5) are necessary for managing various resources. In fact, risks related to scheduling, process management, and resource allocation, influenced by external uncertainties, can negatively impact project performance [57,80]. Therefore, a comprehensive risk management system (S_8) should be developed to identify and control risks through the whole processes of Lean in PC, as supported by Ghosh and Jason [81].

The roles of these Lean strategies have been validated by, but are not limited to, Netland et al. [71]; Anaç et al. [57]; Li et al. [80]; Demirkesen, S., and Bayhan, H.G. [74]; Mostafa et al. [53]; and Lista et al. [73]. However, previous studies have only highlighted their importance without evaluating their priorities. Compared to these studies, the current developed framework considers the interactions between Lean strategies and identifies four levels of prioritization, with emphasis placed on the top levels.

5. Conclusions

This study developed a network-based ISM-MICMAC model to analyze the planning of Lean implementation in line with strategic control and projects' performances under China's PC. This model included a qualitative analysis to identify Lean implementation strategies based on a literature review and experts' interviews and a quantitative analysis via the structural part and the importance part to analyze the interrelationships of Lean implementation. The results revealed that:

1. Lean is systematic engineering, where various implementation strategies are interconnected and mutually influenced into a complex network.
2. The planning of Lean implementation consists of foundation, organizational, technical, and control levels, reflecting the hierarchical order, priorities, and importance for the successful Lean implementation.
3. Efficient measures of Lean implementation are establishing a top-level Lean promotion group, cultivating participants Lean awareness and skills, constructing a comprehensive standard system, selecting the appropriate technologies, enhancing inter-external collaboration, continuously optimizing plans and processes, and building a risk monitoring system.

Managerial implications are summarized. This study is expected to lead stakeholders in overcoming challenges in the Lean implementation process and guide them about success parameters for strategy and performance to consider and prioritize tasks when implementing Lean in PC. Firstly, the 17 Lean implementation strategies and their interactions are revealed to successfully implement Lean for stakeholders in PC, China. Secondly, selecting the appropriate Lean tools and information technologies is crucial, which is based on the foundation of establishing a top-level management team and fostering Lean culture. Thirdly, it is important to build a standard system of processes and activities, enhance the inter-external collaboration, and continuously improve the processes in response to changes.

The contribution of this study is twofold. From a theoretical view, it has explored the effective Lean in PC by an innovative network-based analysis of the interrelationships of Lean implementation strategies to enrich the existing knowledge body of PC performance. This is not only an application of existing theories of Lean, PC, ISM-MICMAC, and complex networks but also a theoretical enrichment in the field of project management. From a practical point of view, the proposed planning could serve as a road map for stakeholders to improve strategic control and projects' performance. This study also provides clues for the advancement of digital construction, particularly through improving the processes of PC projects. In fact, Lean is the basis of transformation towards digital construction.

Admittedly, this study has limitations. Firstly, the validation of the findings in real-world projects should be considered, as this will strengthen the authority of the network-based model. Secondly, the analysis was measured from a static perspective, while Lean may evolve dynamically with the development of PC. Future studies could incorporate a longitudinal approach to capture the changes in Lean and PC development. Lastly, it should be noted that this study specifically pertained to the Lean PC projects in China, with a focus on the initial development phase. However, this network-based analysis is applicable in developed countries, making it conducive to cross-country comparisons.

Author Contributions: Conceptualization, P.D. and C.S.; Software, Methodology, Validation, P.D.; resources, Z.N.; writing—original draft preparation, P.D. and S.J.; writing—review and editing, L.G. and P.D.; Supervision, P.D. and Z.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets in the current study are available from the corresponding author upon reasonable request.

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

Appendix A

The SSIM of Lean implementation strategies.

Strategy	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_1	Z	Z	W	W	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	—
S_2	Z	Z		X	Y	Z	Z	W	Z	Z	Z	Z	Z	Z	Z	—	
S_3	Z	Z	X	X	Y	Z	Z	W	Z	Z	Z	Z	Z	Z	—		
S_4	Z	Z	Z	Z	Z	Z	Z	Z	Y	Z	Z	Z	Z	—			
S_5	Z	Z	Z	Z	Z	Z	Y	Z	Z	W	Z	Z	—				
S_6	X	Z	Z	Z	Z	X	W	X	W	Z	Y	—					
S_7	X	Z	Z	Z	Z	X	W	X	W	Z	—						
S_8	Z	Z	Z	Z	Z	Z	X	Z	X	—							
S_9	Z	Z	Z	Z	Z	Z	Y	Z	—								
S_{10}	W	Y	Z	Z	X	Y	Z	—									
S_{11}	Z	Z	Z	Z	Z	Z	—										
S_{12}	W	Z	Z	Z	Z	—											
S_{13}	Z	Z	X	X	—												
S_{14}	Z	Z	Y	—													
S_{15}	Z	Z	—														
S_{16}	Z	—															
S_{17}	—																

Appendix B

The AM of Lean implementation strategies.

Strategy	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
S_2	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
S_3	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
S_4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
S_5	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
S_6	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0
S_7	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0
S_8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_9	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0
S_{10}	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	1	1
S_{11}	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0
S_{12}	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	1
S_{13}	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S_{14}	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0
S_{15}	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0
S_{16}	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S_{17}	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0

Appendix C

The RM of Lean implementation strategies.

Strategy	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S_2	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1
S_3	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1
S_4	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0
S_5	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0
S_6	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0
S_7	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0
S_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_9	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0
S_{10}	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
S_{11}	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0
S_{12}	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
S_{13}	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1
S_{14}	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S_{15}	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S_{16}	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
S_{17}	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	1

Appendix D

The DRP and DEP values of Lean implementation strategies based on RM.

Strategy	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	DRP
S_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	17
S_2	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	14
S_3	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	14
S_4	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	5
S_5	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	5
S_6	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	7
S_7	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	7
S_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
S_9	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	5
S_{10}	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	11
S_{11}	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	5
S_{12}	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	11
S_{13}	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	14
S_{14}	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
S_{15}	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
S_{16}	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	11
S_{17}	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	1	8
DEP	1	6	6	16	16	12	12	17	16	9	16	9	6	3	3	9	10	

Appendix E

D among the 17 Lean implementation strategies.

d_{SiSj}	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_1	-	2	2	6	6	4	4	6	5	3	5	4	2	1	1	4	4
S_2	∞	-	2	4	4	2	2	4	3	1	3	2	1	∞	∞	2	2
S_3	∞	2	-	4	4	2	2	4	3	1	3	2	1	∞	∞	2	2
S_4	∞	∞	∞	-	3	∞	∞	2	3	∞	2	∞	∞	∞	∞	∞	∞
S_5	∞	∞	∞	3	-	∞	∞	1	2	∞	1	∞	∞	∞	∞	∞	∞
S_6	∞	∞	∞	2	2	-	1	2	1	∞	1	∞	∞	∞	∞	∞	∞

d_{SiSj}	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_7	∞	∞	∞	2	2	1	-	2	1	∞	1	∞	∞	∞	∞	∞	∞
S_8	∞	∞	∞	∞	∞	∞	∞	-	∞	∞	∞	∞	∞	∞	∞	∞	∞
S_9	∞	∞	∞	1	2	∞	∞	1	-	∞	1	∞	∞	∞	∞	∞	∞
S_{10}	∞	∞	∞	3	3	1	1	3	2	-	2	1	∞	∞	∞	1	1
S_{11}	∞	∞	∞	2	1	∞	∞	1	1	∞	-	∞	∞	∞	∞	∞	∞
S_{12}	∞	∞	∞	3	3	2	1	3	2	1	2	-	∞	∞	∞	2	1
S_{13}	∞	1	1	4	4	2	2	4	3	1	3	2	-	∞	∞	2	2
S_{14}	∞	1	1	5	5	3	3	5	4	2	4	3	1	-	1	3	3
S_{15}	∞	2	1	5	5	3	3	5	4	2	4	3	1	1	-	3	3
S_{16}	∞	∞	∞	4	4	2	2	4	3	1	3	2	∞	∞	∞	-	2
S_{17}	∞	∞	∞	3	3	1	1	3	2	∞	2	∞	∞	∞	∞	∞	-

Appendix F

The ICM for the ISM network with 17 Lean implementation strategies.

ICV_{SiSj}	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_1	1	0	0	0	0	0	0	0	0	0	0	0	0	0.329	0.263	0	0
S_2	0	1	0	0	0	0	0	0	0	0.526	0	0	0.329	0	0	0	0
S_3	0	0	1	0	0	0	0	0	0	0.526	0	0	0.329	0	0	0	0
S_4	0	0	0	1	0	0	0	0	0.329	0	0	0	0	0	0	0	0
S_5	0	0	0	0	1	0	0	0.197	0	0	0.329	0	0	0	0	0	0
S_6	0	0	0	0	0	1	0.394	0	0.329	0	0.329	0	0	0	0	0	0
S_7	0	0	0	0	0	0.394	1	0	0.329	0	0.329	0	0	0	0	0	0
S_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_9	0	0	0	0.066	0	0	0	0.197	1	0	0.329	0	0	0	0	0	0
S_{10}	0	0	0	0	0	0.394	0.394	0	0	1	0	0.263	0	0	0	0.066	0.263
S_{11}	0	0	0	0	0.131	0	0	0.197	0.329	0	1	0	0	0	0	0	0
S_{12}	0	0	0	0	0	0.394	0.394	0	0	0.526	0	1	0	0	0	0	0.263
S_{13}	0	0.197	0.197	0	0	0	0	0	0	0.526	0	0	1	0	0	0	0
S_{14}	0	0.197	0.197	0	0	0	0	0	0	0	0	0	0.329	1	0.263	0	0
S_{15}	0	0	0.197	0	0	0	0	0	0	0	0	0	0.329	0.329	1	0	0
S_{16}	0	0	0	0	0	0	0	0	0	0.526	0	0	0	0	0	1	0
S_{17}	0	0	0	0	0	0.394	0.394	0	0	0	0	0	0	0	0	0	1

Appendix G

The IEM for the ISM network with 17 Lean implementation strategies.

IEV_{SiSj}	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
S_1	0.374	0	0	0	0	0	0	0	0	0	0	0	0	0.149	0.111	0	0
S_2	0	0.401	0	0	0	0	0	0	0	0.230	0	0	0.142	0	0	0	0
S_3	0	0	0.401	0	0	0	0	0	0	0.230	0	0	0.142	0	0	0	0
S_4	0	0	0	0.104	0	0	0	0	0.072	0	0	0	0	0	0	0	0
S_5	0	0	0	0	0.177	0	0	0	0	0	0.072	0	0	0	0	0	0
S_6	0	0	0	0	0	0.281	0.111	0	0.072	0	0.072	0	0	0	0	0	0
S_7	0	0	0	0	0	0.111	0.281	0	0.072	0	0.072	0	0	0	0	0	0
S_8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_9	0	0	0	0.007	0	0	0	0	0.219	0	0.072	0	0	0	0	0	0
S_{10}	0	0	0	0	0	0.111	0.111	0	0	0.438	0	0.099	0	0	0	0.018	0.066
S_{11}	0	0	0	0	0.023	0	0	0	0.072	0	0.219	0	0	0	0	0	0
S_{12}	0	0	0	0	0	0.111	0.111	0	0	0.230	0	0.375	0	0	0	0	0.066
S_{13}	0	0.079	0.079	0	0	0	0	0	0	0.230	0	0	0.432	0	0	0	0
S_{14}	0	0.079	0.079	0	0	0	0	0	0	0	0	0	0.142	0.454	0.111	0	0
S_{15}	0	0	0.079	0	0	0	0	0	0	0	0	0	0.142	0.149	0.423	0	0
S_{16}	0	0	0	0	0	0	0	0	0	0.230	0	0	0	0	0	0.276	0
S_{17}	0	0	0	0	0	0.111	0.111	0	0	0	0	0	0	0	0	0	0.250

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