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Assessing and Prioritising Delay Factors of Prefabricated Concrete Building Projects in China

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Abstract: Prefabricated construction has been widely accepted as an alternative to conventional cast-in-situ construction, given its improved performance. However, prefabricated concrete building projects frequently encounter significant delays. It is, therefore, crucial to identify key factors affecting schedule and explore strategies to minimise the schedule delays for prefabricated concrete building projects. This paper adopts the decision-making trial and evaluation laboratory (DEMATEL) model and analytic network process (ANP) method to quantify the cause-and-effect relationships and prioritise the key delay factors in terms of their importance in the Chinese construction industry. The DEMATEL model evaluates the extent to which each factor impacts other factors. The quantified extents are then converted into a prioritisation matrix through ANP. The delay factors of prefabricated construction projects are selected and categorised based on a literature review and an expert interview. Questionnaires are then implemented to collect the data. The results reveal that the issue of inefficient structural connections for prefabricated components is found to be the most significant factor and most easily affected by other delay factors. This research also suggests prioritising major delay factors, such as 'lack of communication among participants' and 'low productivity', in the Chinese construction industry during scheduling control. Overall, this research contributes an assessment framework for decision making in the scheduling management of prefabricated construction.

Keywords: construction delay; prefabricated construction; decision-making trial and evaluation laboratory (DEMATEL); analytic network process (ANP); multi-criteria decision making

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1. Introduction

Prefabricated construction refers to the practice of designing and fabricating building elements in manufacturing factories, transporting the elements to construction sites, and assembling the elements to a greater degree of finish for rapid site assembly compared to traditional piecemeal on-site construction [1,2]. Thus, interchangeable terminologies associated with prefabricated construction in the existing literature include off-site construction [3], off-site prefabrication [4], off-site manufacturing construction [5], and off-site production [6]. Prefabricated concrete construction is considered a widely accepted alternative to conventional cast-in-situ concrete construction since it offers numerous benefits for investors and contractors, such as higher speed of construction, enhanced quality outputs, higher tolerances, lower costs, reduced labour re-works on-site, and safer construction environments [7–9]. From the perspective of environmental sustainability, prefabricated concrete construction benefits in waste reduction [10], facilitates the reuse of some components [11] and reduces water consumption [12]. The above-mentioned merits have significantly contributed to improving construction industries in developed and developing countries [13]. In particular, precast technologies have been greatly developed to meet the requirements of sustainability and housing demand in China [14]. China has also embarked on several initiatives to promote prefabrication [15]. However, in comparison to conventional on-site construction, there are also notable disadvantages that should be considered, such as structural changeability, transportation restrictions, and span limits [16]. In particular, prefabricated concrete construction requires increased and more detailed coordination at all stages of a project (because of more construction phases, more complicated construction techniques, and more stakeholders), which increases the difficulty in progress monitoring and planning for construction management tasks.

Unlike the traditional construction methods, researchers and engineers are advised to pay particular attention to schedule risks of prefabrication construction projects before the construction stage [17]. For example, Li et al. [18] utilised a fuzzy analytical hierarchy process approach for ranking project risks associated with modular construction. The results revealed that the control schedule in the design stage is an important factor with respect to project duration owing to a relatively high weighting value. Also, few studies have investigated stakeholder-related risks and their cause-and-effect relationships prior to the construction stage. Therefore, Li et al. [17] employed a social network analysis to recognise and investigate the underlying network of stakeholder-associated risk factors in prefabrication housing construction projects. They emphasised the information-related risks and indicated that the design information gap between designers and manufacturers may result in frequent delay in projects [19]. Moreover, the efficient manufacturing of building elements is vital to delivery deadlines. Taghaddos et al. [20] adopted a simulation-based auction protocol framework to effectively schedule modular construction projects with limited data available. To monitor and visualise the work progress of off-site activities, Building Information Modelling is considered an effective and practical tool [21].

Overall, delays frequently occur on prefabricated concrete building projects, despite enormous efforts toward project schedule estimation and control. Researchers have also realised that construction delay is a primary barrier to the adoption of prefabricated construction in many nations [22]. It is, therefore, worthwhile to explore some strategies for avoiding schedule delays in prefabricated building projects and minimising schedule delay risks in the Chinese construction industry. In addition, previous research confronts several challenges. First, there is a lack of implementing mathematical models in the comprehensive investigation of relevant delay factors in prefabricated building projects, especially in the Chinese construction industry. Second, there is an urgent need to rank the delay factors and quantify relationships among the factors for prefabricated building projects.

Recently, several studies have applied multi-criteria decision making techniques, such as Technique for Order Preference by Similarity, Analytic Hierarchy Process (AHP) and Data Envelopment Analysis, for project risk assessment [23–26]. Analytic network process (ANP) is a generalisation of AHP, and is capable of making more accurate predictions with better priority calculations in cases of networks with dependent criteria [27]. Clearly, ANP can better provide benefits in calculating criteria priorities and their relations. Meanwhile, decision-making trial and evaluation laboratory (DEMATEL) is a useful method for analysing and quantifying cause-effect relationships. Thus, integrating DEMATEL with ANP can effectively identify the critical attributes of strategy implementation and evaluate weights of the business environment criteria [28]. Consequently, many fields are showing increasing interest in utilising the DEMATEL-ANP method for multi-criteria decision-making. For example, Tseng and Lin [29] adopted a DEMATEL-ANP method to find an appropriate solution regarding municipal solid waste management in metropolitan Manila. In 2011, Tseng [30] developed the DEMATEL-ANP method to evaluate knowledge management capability of a firm, while the same methodology was also used to select health-care organisations [31]. Moreover, Yeh and Huang [32] examined the key factors in determining location selections for wind farms based on the combination method. More recently, the method was also applied in the renewable energy resources selection in Turkey [28]. However, a synthesised risk assessment based on the combination method has not yet been established in construction projects of prefabricated concrete buildings. Thus, this paper adopts the DEMATEL-ANP method to quantify cause-and-effect relationships of delay factors and prioritise them in terms of their importance. The assessment measure can be beneficial for decision makers to minimise schedule delay risks in prefabricated concrete building projects.

2. Schedule Management in Prefabricated Building Projects

2.1. Identification of Project Processes and Phases

To manage the schedule performance of a prefabricated concrete building project, it is essential to investigate its entire project process and highlight the differences with conventional on-site construction. Although prefabricated construction can be categorised into modular, panelised, prefabricated, and processed materials construction in terms of the extent of off-site production [33], their construction processes can be summarised in a flowchart, as presented in Figure 1.

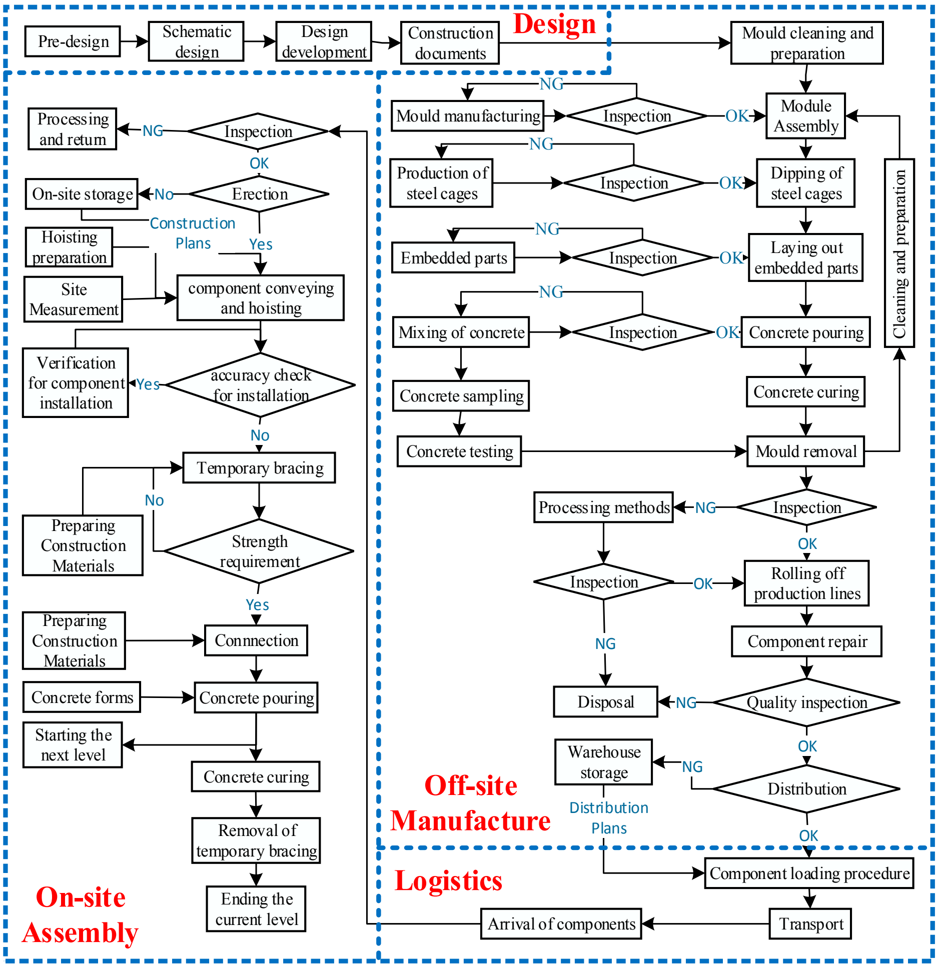

Figure 1. Flowchart of prefabricated construction process.

According to the definition of prefabricated construction presented in Section 1 above, a typical project can be divided into four phases: design, off-site manufacture, logistics, and on-site assembly. During the design phase, the schematic design often produces rough drawings of a site plan, floor plans, and elevations. The results are collected and taken one step further to specify components and produce drawings. During the off-site manufacturing phase, steel moulds are cleaned to remove residual contamination and concrete lumps. Steel cages and embedded parts are then placed into moulds after the module assembly. After mixing, the concrete is immediately placed in the moulds and cured. After quality inspection, components are delivered to the storage facility or transported to construction sites. Before the actual erection of the components, several procedures should be carried out, such as the site accessibility check, crane capacity check, and sample measurement. The components are then hoisted to their designated locations and adjusted into their positions. Generally, non-shrink mortar is used to seal any gaps. The joint rebars are then installed and forms are set up to carry out the concrete casting. The temporary bracing is removed after the concrete has cured. Overall, the prefabricated construction process differs greatly from conventional on-site construction.

2.2. Identification of Construction Delay Factors

To explore strategies for minimising schedule delay risks, it is important to identify the main delay factors in prefabricated building projects, prioritise key factors, and quantify their relationships. Therefore, a simple searching procedure is implemented by searching delay-factor-related and schedule-risk-related papers within the high-impact construction journals suggested by Wing [34]. The literature limited to the last ten years (2009–2018) is then summarised in Table 1 and used to identify various delay factors.

Table 1. Literature of construction schedule performance within selected journals.

Journals	Number of Reviewed Papers	Scholarly Publications
Construction Management and Economics	2	[35,36]
Journal of Construction Engineering and Management	10	[37–46]
Engineering, Construction and Architectural Management	9	[47–55]
Journal of Management in Engineering	12	[56–67]
International Journal of Project Management	5	[68–72]
Automation in Construction	2	[73,74]

Once the delay factors are identified, elements irrelevant to prefabricated concrete building projects and rarely-occurring causes are excluded in this research through an expert interview. Table 2 displays the key factors affecting the schedule of prefabricated concrete buildings from the aspects of construction techniques, workforce, resources, machinery, clients, contractors, and external conditions.

(1) Construction Techniques: Although off-site construction significantly reduces the on-site construction workload, it is difficult to cope with various prefabricated components. The components are also relatively large and heavy, which requires sufficient site space, and the appropriate schedule control for hoisting and installation. In addition, high-precision installation techniques are crucial for prefabricated construction, especially complicated connection processes [16]. Thus, technique-related risk factors, including inappropriate site management and low-level installation technologies, inevitably affect the project progress of prefabricated buildings.

(2) Workforce: There is less workforce requirement in prefabricated construction, compared with traditional on-site construction. However, the current prefabricated construction process is not technologically advanced and relies on intensive labour, and the labour requires machine-oriented skills both on site and in the manufacturing process. Inadequate worker experience and poor performance have significant impacts on project progress.

(3) Resources: Material shortage is a potential source of construction delay. The major cause of material shortage is that demand exceeds supply. Offsite prefabricated systems vary depending on the sizes of prefabricated components, which affect the need for on-site construction. Another cause of material shortage could be damage to stored components.

(4) Machinery: Lack or unavailability of equipment is a significant factor that contributes to delays. In the construction stage, some contractors may experience the lack of machinery to produce work because of high cost and equipment failure.

(5) Contractors: Time estimates aim to manage and structure projects. Ineffective planning and scheduling by contractors is another key driver in delaying projects. Poor site management and supervision also contribute to project delays. Large prefabricated sections may require heavy-duty cranes as well as precision measurement and handling to place in position. Clearly,

rehandling components greatly impacts the scheduling performance. Occasionally, components are returned to the manufacturers due to design errors and damaged components.

(6) Clients: Construction delay may occur if clients make changes to the design during the construction period or present additional requirements. In such cases, contractors cannot carry out their work until the updated drawings are issued by architects.

(7) External Conditions: Weather is a factor that can influence delays throughout the entire project since weather conditions interfere with planned activities such as on-site concreting tasks. Weak regulation and unstable policies are also seen as causes of delay. For example, customs delays at border crossings may occur when transporting components internationally.

Table 2. Key factors affecting project progress in prefabricated building projects.

Dimensions	Factors
D1 Construction Techniques	F11 Low-precision installation techniques F12 Improper lifting operations F13 Insufficient site space to layout
D2 Workforce	F21 Inadequate worker experience F22 Low productivity F23 Insufficient proficiency
D3 Resources	F31 Shortage and delay in material supply F32 Damage to stored components
D4 Machinery	F41 Equipment failure F42 Vehicle and equipment unavailability
D5 Clients	F51 Inefficient decision-making F52 Additional requirements
D6 Contractors	F61 Improper construction planning and schedule design F62 Wrong delivery requirements and routes F63 Poor site layout F64 Lack of communication among participants F65 Information gaps among companies F66 Rehandling components F67 Inefficient structural connections F68 Return to manufacturers owing to design errors F69 Re-manufacturing owing to component damage
D7 External Conditions	F71 Policy uncertainty F72 Severe weather F73 Energy and water supply failure, transportation disruption

3. DEMATEL–ANP Method

In order to quantify their cause-and-effect relationships and prioritise the key delay factors in terms of their importance, the research presented in this paper applies the combination method to the prefabricated construction process.

Step 1: An average direct-relation matrix is produced. Experts are interviewed to provide pairwise comparisons in terms of the direct influence between the criteria with an influence scale of 0 (no influence), 1 (low influence), 2 (medium influence), 3 (high influence), and 4 (very high influence). It is assumed that there are K respondent experts and N factors. A direct-relation matrix of $N \times N$ can be produced by each expert, as expressed in Equation (1). $\boldsymbol{A}_{ij}$ represents the influential level of Factor *i* to Factor *j*, but its value will be equal to zero for the self-influence of factors when *i* = *j*.

$$\boldsymbol{A} = \left(a_{ij}\right)_{n\times n} = \begin{bmatrix} a_{11}=0 & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22}=0 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn}=0 \end{bmatrix} (i\ and\ j \in 1,\ 2,\ \ldots.n) \tag{1}$$

Step 2: The average matrix is normalised. Equation (2) is used to convert the direct-relation matrix to the standardised impact matrix $\boldsymbol{D}$.

$$\boldsymbol{D} = z\boldsymbol{A},\ \text{where z} = \min\left\{1/max_i \sum_{j=1}^{n} a_{ij}, 1/max_j \sum_{i=1}^{n} a_{ij}\ \right\} \tag{2}$$

Step 3: The total influence matrix $\boldsymbol{T}$ is determined, where $\boldsymbol{T} = \left(t_{ij}\right)_{n\times n},\ when\ i\ and\ j \in 1,\ 2,\ \ldots.n$. The element t_{ij} denotes the direct and indirect effects of Factor *i* on Factor *j*.

$$\begin{gathered} \boldsymbol{T} = \lim_{K\to\infty}\left(\boldsymbol{D}+\boldsymbol{D}^2+\boldsymbol{D}^3+\ldots+\boldsymbol{D}^h\right) = \lim_{K\to\infty}\boldsymbol{D}\left(\boldsymbol{I}-\boldsymbol{D}^h\right)(\boldsymbol{I}-\boldsymbol{D})^{-1} = \boldsymbol{D}(\boldsymbol{I}-\boldsymbol{D})^{-1}, \\ when\ \lim_{K\to\infty}\boldsymbol{D}^h = [0]_{n\times n} \end{gathered} \tag{3}$$

where $\boldsymbol{I}$ is defined as the identity matrix.

Step 4: The levels of influence and effects are obtained based on the row sum, r_i, and column sum, c_j, of the matrix $\boldsymbol{T}$.

$$r_i = \sum_{j=1}^{n} t_{ij}\ and\ c_j = \sum_{i=1}^{n} t_{ij} \tag{4}$$

Here, r_i represents the sum of the *i*th row in the total influence matrix $\boldsymbol{T}$, and displays the sum the direct and indirect influences that Factor *i* gives to all other factors. Similarly, c_j represents the sum of the *j*th column in the total influence matrix $\boldsymbol{T}$, and displays the sum of direct and indirect influences that Factor *j* receives from all other factors. Furthermore, let $i = j$ and $i, j \in \{1,\ 2, \ldots,\ n\}$. $r_i + c_i$ provides an index of the strengths of influences given and received. That is, $r_i + c_i$ shows the degree of total influences Factor *i* has in this system. The difference $r_i - c_i$ shows the net effect that Factor *i* contributes to the problem. Therefore, if $r_i - c_i$ is positive, then Factor *i* has a net influence on the other factors, and if $r_i - c_i$ is negative, then Factor *i* is, on the whole, being influenced by the other factors [75,76].

Step 5: The total influence matrix $\boldsymbol{T}$ is divided into $\boldsymbol{T}_D$ based on the dimensions and $\boldsymbol{T}_C$ based on the factors.

$$T_c = \begin{array}{cc cccc} & & D_1 & D_2 & \cdots & D_n \\ & & C_{11}\cdots C_{1m_1} & C_{21}\cdots C_{2m_2} & & C_{n1}\cdots C_{nm_n} \\ D_1 & \begin{matrix} C_{11} \\ C_{12} \\ \vdots \\ C_{1m_1} \end{matrix} & \boldsymbol{T}_C^{11} & \boldsymbol{T}_C^{12} & \cdots & \boldsymbol{T}_C^{1n} \\ D_2 & \begin{matrix} C_{21} \\ C_{22} \\ \vdots \\ C_{2m_2} \end{matrix} & \boldsymbol{T}_C^{21} & \boldsymbol{T}_C^{22} & \cdots & \boldsymbol{T}_C^{2n} \\ & \vdots & \vdots & \vdots & \ddots & \vdots \\ D_n & \begin{matrix} C_{n1} \\ C_{n2} \\ \vdots \\ C_{nm_n} \end{matrix} & \boldsymbol{T}_C^{n1} & \boldsymbol{T}_C^{n2} & \cdots & \boldsymbol{T}_C^{nn} \end{array} \tag{5}$$

$$\boldsymbol{T}_D = \begin{bmatrix} t_D^{11} & t_D^{12} & \cdots & t_D^{1n} \\ t_D^{21} & t_D^{22} & \cdots & t_D^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_D^{n1} & t_D^{n2} & \cdots & t_D^{nn} \end{bmatrix} \tag{6}$$

Step 6: The total influence matrix $\boldsymbol{T}_c$ is normalised by each dimension represented as $\boldsymbol{T}_C^{\alpha}$.

$$\boldsymbol{T}_C^{\alpha} = \begin{bmatrix} T_C^{\alpha 11} & T_C^{\alpha 12} & \cdots & T_C^{\alpha 1n} \\ T_C^{\alpha 21} & T_C^{\alpha 22} & \cdots & T_C^{\alpha 2n} \\ \vdots & \vdots & \ddots & \vdots \\ T_C^{\alpha n1} & T_C^{\alpha n2} & \cdots & T_C^{\alpha nn} \end{bmatrix} \tag{7}$$

Step 7: The unweighted super-matrix, $\boldsymbol{W}$, of the delay factors affecting the schedule performance of prefabricated construction is obtained.

$$\boldsymbol{W} = (\boldsymbol{T}_C^{\alpha})' \tag{8}$$

Step 8: The weighted normalised super-matrix, $\boldsymbol{W}^{\alpha}$, is calculated.

$$\boldsymbol{T}_D^{\alpha} = \begin{bmatrix} t_D^{11}/d_1 & t_D^{12}/d_1 & \cdots & t_D^{1n}/d_1 \\ t_D^{21}/d_2 & t_D^{22}/d_2 & \cdots & t_D^{2n}/d_2 \\ \vdots & \vdots & \ddots & \vdots \\ t_D^{n1}/d_n & t_D^{n2}/d_n & \cdots & t_D^{nn}/d_n \end{bmatrix} = \begin{bmatrix} t_D^{\alpha 11} & t_D^{\alpha 12} & \cdots & t_D^{\alpha 1n} \\ t_D^{\alpha 21} & t_D^{\alpha 22} & \cdots & t_D^{\alpha 2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_D^{\alpha n1} & t_D^{\alpha n2} & \cdots & t_D^{\alpha nn} \end{bmatrix} \tag{9}$$

in which $d_i = \sum_{j=1}^{n} t_D^{ij}$,

$$\boldsymbol{W}^{\alpha} = \boldsymbol{T}_D^{\alpha} \boldsymbol{W} \tag{10}$$

Step 9: The overall priorities are calculated using the limiting process method. The weighted super-matrix can be raised to limiting values until the super-matrix has converged and becomes a long-term, stable super-matrix acquiring global priority vectors with a sufficiently large power, ρ, namely

$$\lim_{\rho \to \infty} (\boldsymbol{W}^{\alpha})^{\rho} \tag{11}$$

4. Data Collection and Pro-Process

The delay factors of prefabricated construction have been identified in Section 2.2. Regarding the questionnaires, Table 3 shows the demographic information of participants. The DEMATEL does not require a large number of respondents [77], and in this research there are thirty respondents from China's prefabricated construction industry, namely $K = 30$, that consist of six academic experts in construction management, five clients, five contractors, eight manufacturing and logistics experts, four experts from construction firms, and two government officers. Various insights with regard to delay factors were considered in this research. The mix of different industrial backgrounds was well proportioned in the sample. Government officers were considered, since local governments also paid much attention to prefabricated construction. Academic experts' opinions were also taken into account in this research. Moreover, the participants have at least 5 years' working experience and 20% of the participants have the experience of more than 20 years in prefabricated construction.

Table 3. Demographic information of the participants.

	Experience (Years)				Job Background					
Description	**<5**	**5–10**	**10–20**	**>20**	**Universities**	**Clients**	**Main Contractors**	**Manufacturing and Logistics**	**Assembly Firms**	**Government Departments**
Number	8	9	7	6	6	5	5	8	4	2
Percentage	27%	30%	23%	20%	20%	17%	17%	26%	13%	7%

First, introductory conversations and email contacts were made with each respondent to explain and make the objectives of the research clear. Second, the experts could discuss with each other and express their opinions before the assessment. Third, each expert made an evaluation for the relative influence of the criteria using pairwise comparisons. As mentioned previously, the responses range from 0 to 4, namely, 0 (no influence), 1 (low influence), 2 (medium influence), 3 (high influence), and 4 (very high influence). Therefore, the average direct-relation matrix can be listed as presented in Table 4.

Table 4. Average direct-relation matrix.

	F11	**F12**	**F13**	**F21**	**F22**	**F23**	**F31**	**F32**	**F41**	**F42**	**F51**	**F52**	**F61**	**F62**	**F63**	**F64**	**F65**	**F66**	**F67**	**F68**	**F69**	**F71**	**F72**	**F73**
F11	0	0	0	0	1	0	0	0	0	0	1	1	1	2	2	0	0	2	4	0	0	0	0	0
F12	0	0	0	0	1	0	0	0	0	0	0	0	1	0	3	0	0	4	3	0	1	0	0	0
F13	0	0	0	0	1	0	2	2	0	3	0	0	1	3	4	0	0	4	0	0	1	0	0	0
F21	0	0	0	0	4	4	1	1	1	2	0	0	4	4	4	1	0	3	4	2	3	0	0	0
F22	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	1	0	0	4	0	0	0	0	0
F23	0	0	0	0	4	0	2	2	2	2	0	0	0	3	2	1	0	1	4	0	1	0	0	0
F31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
F32	0	0	0	0	2	0	4	0	0	0	0	0	0	0	0	0	0	3	3	0	1	0	0	0
F41	0	0	0	0	2	0	4	1	0	4	0	0	0	0	0	0	0	0	3	0	1	0	0	0
F42	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
F51	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	0
F52	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0
F61	3	2	3	0	3	0	4	0	0	4	2	0	0	3	0	3	0	4	3	1	0	0	0	0
F62	0	0	0	0	4	0	3	0	0	3	0	0	0	0	0	0	0	4	0	0	2	0	0	0
F63	0	4	4	0	3	0	0	0	0	3	0	0	0	0	0	0	0	4	4	0	0	0	0	0
F64	0	0	0	0	4	0	4	0	0	4	4	0	3	3	4	0	0	4	4	0	0	0	0	0
F65	0	0	0	0	4	0	3	0	0	3	3	0	3	3	3	4	0	4	4	1	0	0	0	0
F66	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	3	0	0	0
F67	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0
F68	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
F69	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0
F71	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F72	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	2	0	2	0	0	0
F73	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	2	0	2	0	0	0

It can be observed that the delay factors under Dimension 7, including F71, F72, and F32, do not result from other factors from the viewpoints of the experts. For example, weather conditions and power outages are not affected by any procedures of prefabricated construction, but they may result in the shortage of material supply and equipment unavailability. Similarly, few factors possibly produce any effects on Factor 21, 'inadequate worker experience'.

In addition, the experts consider that the assembly procedures may become time-consuming due to various reasons, such as improper construction planning, irrational schedule design, unfeasible site layout, inadequate worker experience, and insufficient proficiency.

5. Results and Analysis

5.1. DEMATEL Analysis

To determine the influence by degree of the relationships among delay factors, the DEMATEL–ANP procedures are implemented in this research. In terms of Equation (4), the sum of effects of Factor i on all other factors (r_i) and the sum of effects implemented on Factor i from all other factors (c_i) are listed in Table 5. Similarly, dimension-related indicators are also listed in Table 5.

As discussed in Section 3, $r_i + c_i$ indicates the degree of importance that Factor i has in a problem, whereas the difference of $r_i - c_i$ specifies the net effect that Factor i contributes to a problem. An influential network-relationship map for the seven dimensions is depicted in Figure 2 according to values of $r + c$ and $r - c$ in Table 5.

Table 5. Sum of influences given to and received from other factors.

Dimension	r_i	c_i	$r_i + c_i$	$r_i - c_i$	Factor	r_i	c_i	$r_i + c_i$	$r_i - c_i$
D1	0.7791	0.0000	0.7791	0.7791	F11	0.5324	0.1099	0.6423	0.4225
					F12	0.5060	0.2507	0.7566	0.2553
					F13	0.8086	0.2873	1.0959	0.5214
D2	1.0902	0.4306	1.5208	0.6596	F21	1.5553	0.0000	1.5553	1.5553
					F22	0.3648	1.5282	1.8930	−1.1634
					F23	0.8845	0.1641	1.0486	0.7205
D3	0.3845	1.1627	1.5473	−0.7782	F31	0.0928	1.5063	1.5990	−1.4135
					F32	0.4174	0.5552	0.9726	−0.1378
D4	0.4053	0.8943	1.2996	−0.4890	F41	0.4761	0.0876	0.5637	0.3885
					F42	0.2005	1.5358	1.7363	−1.3353
D5	0.3845	0.9712	1.3558	−0.5867	F51	0.3079	0.3286	0.6365	−0.0207
					F52	0.1826	0.0292	0.2118	0.1533
D6	1.4995	1.2988	2.7983	0.2007	F61	1.3253	0.3920	1.7173	0.9333
					F62	0.5303	0.6578	1.1881	−0.1276
					F63	0.8151	0.6853	1.5005	0.1298
					F64	1.2819	0.3460	1.6279	0.9359
					F65	1.4101	0.0699	1.4800	1.3402
					F66	0.3298	1.4486	1.7784	−1.1188
					F67	0.1752	2.4292	2.6043	−2.2540
					F68	0.1610	0.1174	0.2785	0.0436
					F69	0.2460	0.8122	1.0583	−0.5662
D7	0.2146	0.0000	0.2146	0.2146	F71	0.1811	0.0000	0.1811	0.1811
					F72	0.3085	0.0000	0.3085	0.3085
					F73	0.2481	0.0000	0.2481	0.2481

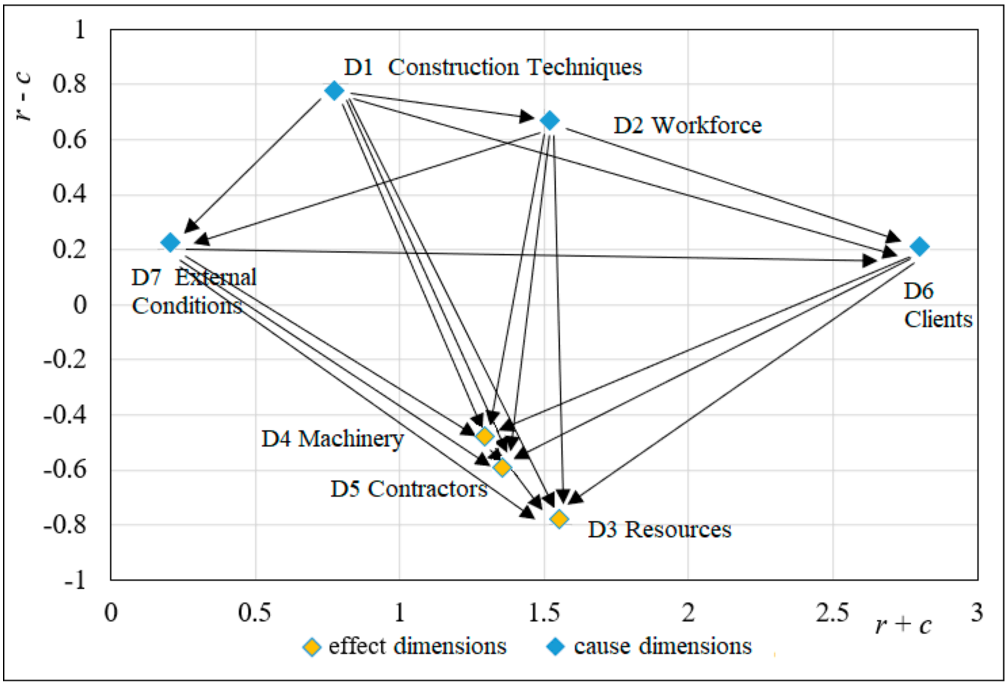

Figure 2. Influential network-relationship map for dimensions.

The seven dimensions influence mutually. Arrows are pointed to dimensions with low y-axis values from dimensions with high y-axis values. Thus, 'construction techniques' (D1) affects 'workforce' (D2), 'external conditions' (D7), 'contractors' (D6), 'machinery' (D4), 'clients' (D5) and 'resources' (D3), namely, D1 $\rightarrow \{$D2, D7, D6, D4, D5, D3$\}$. Similarly, D2 $\rightarrow \{$D7, D6, D4, D5, D3$\}$, D7 $\rightarrow \{$D6, D4, D5, D3$\}$, D6 $\rightarrow \{$D4, D5, D3$\}$, D4 $\rightarrow \{$D5, D3$\}$ and D5 $\rightarrow \{$D3$\}$. This finding suggests that among the dimensions that affect the project progress in prefabricated building projects, 'construction techniques' (D1) exerted the largest influence on the other six dimensions and 'resources' (D3) received the largest influence from the other six dimensions. D1, D2, D6 and D7 are considered cause dimensions, but it is not easy to avoid D1 and D7 at this stage. Strategies can be mainly focused on 'workforce' (D2) and 'contractors' (D6) to eliminate their impacts on D3, D4 and D5 for improving the schedule performance.

In terms of the dispatched-influence value in the seventh column of Table 5, the delay factors can be ranked in the following order: F21, F65, F61, F64, F23, F63, F13, F11, F62, F12, F41, F32, F22, F66, F72, F51, F73, F69, F42, F52, F71, F67, F68, and F31. Factor 21, 'inadequate worker experience', has the most significant impact on the other factors. The results also reveal that 'information gaps among companies' (F65), 'improper construction planning and schedule design' (F61), 'lack of communication among participants' (F64), and 'insufficient proficiency for workers' (F23) are more likely to affect the other factors. For example, on-site assembly as a labour-intensive procedure must currently be completed by construction workers. In China, some construction workers may lack the systematic and professional training for assembly techniques in prefabricated projects because of the cost of training courses. Consequently, construction workers lack the insight into potential issues due to little experience in tackling the existing difficulties. Such insufficient proficiency inevitably leads to low productivity and time-consuming procedures in structural connections for prefabricated components. However, Factor 67, 'inefficient structural connections', with an r-value of 0.1752 has a low probability for influencing other factors.

In terms of the received-influence value in the eighth column of Table 5, the delay factors can be ranked in the following order: F67, F42, F22, F31, F66, F69, F63, F62, F32, F61, F64, F51, F13, F12, F23, F68, F11, F41, F65, F52, F21, F72, F73, and F71. Factor 67, 'inefficient structural connections', is the most easily affected by the most delay factors, especially 'low-precision installation techniques' (F11), 'inadequate worker experience' (F21), and most contractor-related factors. Apart from F67, 'vehicle and equipment unavailability' (F42), 'low productivity' (F22), 'shortage and delay in material supply' (F31), and 'rehandling components' (F66) are also very easily affected by the other investigated factors. A causal diagram is plotted as presented in Figure 3 in terms of the datasets of $r + c$ and $r - c$, which are provided in Table 5.

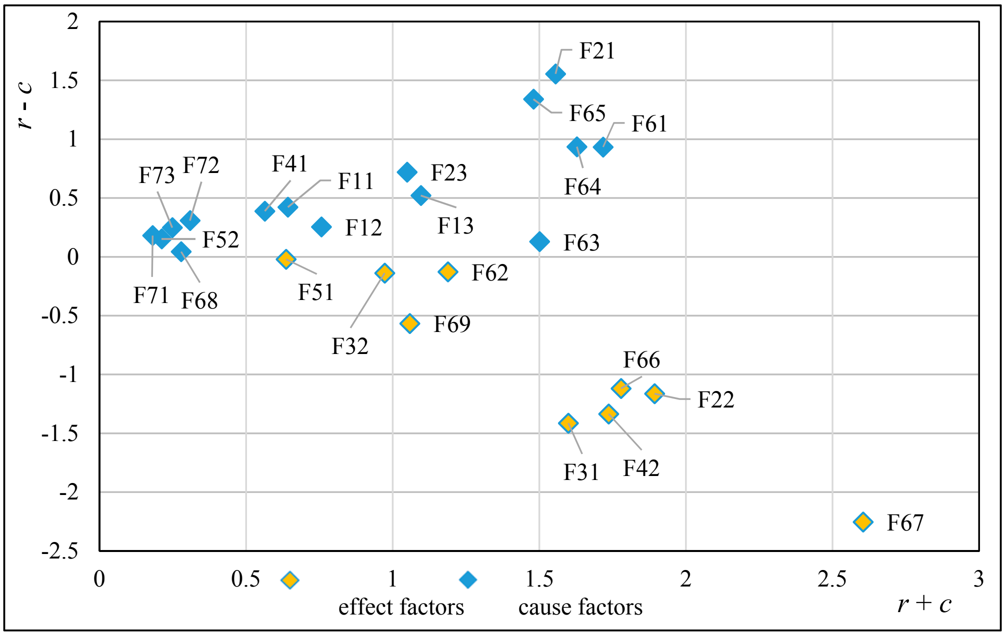

Figure 3. Causal diagram for delay factors in prefabricated construction.

According to the x-axis values, the delay factors can be ranked in the following order: F67, F22, F66, F42, F61, F64, F31, F21, F63, F65, F62, F13, F69, F23, F32, F12, F11, F51, F41, F72, F68, F73, F52, and F71. 'Inefficient structural connections' (F67) is identified as the most import factor as it demonstrates the highest level of interrelationship with other factors. Apart from F67, the figure indicates other core issues for solving the delay problem of prefabricated construction projects, such as 'low productivity' (F22), 'rehandling components' (F66), 'vehicle and equipment unavailability' (F42), 'improper construction planning and schedule design' (F61), and 'lack of communication among participants' (F64). As presented in Figure 3, the investigated delay factors are divided into two cause-and-effect clusters. The effect cluster comprises F51, F62, F32, F69, F66, F22, F42, F31, and F67 owing to negative values of $r - c$. Other factors, including F21, F65, F64, F61, F23, F13, F11, F41, F72, F12, F73, F71, F52, F63, and F68, are included in the cause cluster owing to positive value of $r - c$. The cause-and-effect clusters indicate that eliminating the effects from effect factors can effectively improve the project schedule performance. The solution could be to determine their corresponding cause factors in order to determine mitigation measures. In particular, Factor 21, 'inadequate worker experience', is considered the highest causal factor while Factor 67, 'inefficient structural connections', is the highest effect factor in terms of their y-axis values. Thus, F21 has the most significant impact on the other factors. Avoiding F21 is able to greatly decrease the likelihoods of cause factors occurring for improving the schedule performance.

5.2. ANP Analysis

The ANP method is applied for determining and prioritising the key risk factors for prefabricated construction based on the total influence matrix produced by Equation (3). Table 6 lists the influential weights of 7 dimensions and 24 delay factors that affect the schedule performance in the Chinese construction industry.

Table 6. Influential weights of dimensions and delay factors in prefabricated construction.

Dimension	Influential Weight	Ranking	Factor	Influential Weight	Ranking
D1	0.11456	3	F11	0.00018	16
			F12	0.00026	14
			F13	0.00026	15
D2	0.23992	2	F21	0.00016	17
			F22	0.14886	3
			F23	0.00006	19
D3	0.11316	4	F31	0.08545	6
			F32	0.00466	9
D4	0.08698	5	F41	0.00005	20
			F42	0.05462	7
D5	0.05011	6	F51	0.00074	13
			F52	0.00003	21
D6	0.36358	1	F61	0.08933	5
			F62	0.00225	10
			F63	0.00121	12
			F64	0.10703	4
			F65	0.00222	11
			F66	0.19158	2
			F67	0.27701	1
			F68	0.00014	18
			F69	0.03391	8
D7	0.03169	7	F71	0.00001	23
			F72	0.00002	22
			F73	0.00001	24

Columns 2 and 3 of Table 6 indicate that the contractor-related category should be considered as the most important risk issue in scheduling management since its weight value accounts for 36% and ranks first among the dimensions. Figure 3 also illustrates that the factors under this dimension have the relative importance degrees, in terms of the values of $r + c$. The results reveal that project managers also need to pay particular attention to the workforce-related risk indicators.

To prioritise the risk factors and identify the importance of each factor, a rank of all factors is created according to their final global weights and listed in the rightmost column. The factors under 'external conditions' rank 22nd, 23rd, and 24th (the least influential factors). The DEMATEL–ANP analysis indicates that 'policy uncertainty' (F71), 'severe weather' (F72), and 'energy and water supply failure' (F73) are the least influential elements for two reasons: (1) these issues rarely occur in comparison with other factors in prefabricated construction; and (2) new regulations and rules may experience a period before they come into force. Off-site production is rarely affected by poor weather conditions and on-site construction projects may still be progressing under the moderate weather conditions in China.

For the major delay factors, this research strongly suggests giving the factors high priority and including them in the scheduling control. Factor 67, 'inefficient structural connections', is considered the most significant indicator due to having the highest global weight. Similarly, Figure 3 also indicates the major driving force for solving the construction delay issue is the time-saving in the assembly procedure. Advanced construction techniques could be introduced and visualisation platforms can be applied to predict potential construction issues. Moreover, 'rehandling components' (F66) is shown to be more likely than 'lack of communication among participants' (F64) to result in poor scheduling performance within the contractor-related group. The issue that prefabricated components cannot be managed and placed in position on time results in a time-consuming procedure prior to the on-site assembly. Furthermore, in the workforce category, Factor 22, 'low productivity', has a higher weight than both the 'inadequate worker experience' (F21) and 'insufficient proficiency' (F23) factors, since solving the productivity issue in off-site production and on-site construction have a greater direct impact on the scheduling performance. For example, the productivity can be improved by mechanising prefabrication and construction. In addition, for the secondary delay factors, the research suggests including the four delay factors of the global weights between 0.1 and 0.01 in the scheduling control, such as 'vehicle and equipment unavailability' (F42) and 're-manufacturing owing to component damage' (F69). These factors are indispensable to solving the poor scheduling issue. The result also indicates that the scheduling control could consider the delay factors with global weights between 0.01 and 0.001. The remaining factors do not have the significant importance and are not very necessary to be prioritised in the scheduling control owing to global weights of less than 0.001.

6. Conclusions

Overall, prefabricated construction has been considered a widely accepted alternative to conventional cast-in-situ concrete construction since it is capable of offering numerous benefits for investors and contractors. However, delays frequently occur in prefabricated concrete building projects, despite strong efforts to improve project schedule estimation and control. Thus, the delay factors of prefabricated construction should be identified and analysed to improve its scheduling performance. As one of the multi-criteria decision making techniques, ANP is capable of making accurate calculation of criteria priorities and their relations. Meanwhile, DEMATEL is a useful method for analysing and quantifying cause-effect relationships. Thus, integrating DEMATEL with ANP can effectively identify the critical attributes and evaluate the weights of criteria. Many fields are showing increasing interest in utilising the DEMATEL-ANP method for multi-criteria decision-making; however, a synthesised risk assessment based on the DEMATEL–ANP method had not yet been addressed in construction projects of prefabricated concrete buildings before this research. This paper utilised the combination method for investigating the cause-and-effect relationships among the delay factors and prioritising the key delay factors in terms of their importance in the Chinese construction industry. The DEMATEL model facilitated the evaluation of the extent to which each factor impacts other delay factors. The quantified extents were then converted into a prioritisation matrix through ANP. Twenty-four risk factors have been selected from a literature review and categorised into seven dimensions. Questionnaires have been chosen as data source to assist in the practical application of the method in the prefabricated construction.

The results reveal that 'inadequate worker experience' has the most significant impact on the other factors and 'inefficient structural connections for prefabricated components' is the most easily affected by the most delay factors in the Chinese construction industry. In addition, the global weights indicate that 'inefficient structural connections' is considered the most significant indicator. Other major delay factors, including 'lack of communication among participants' and 'low productivity', should also be included in the scheduling control. Overall, this research contributes an assessment framework for decision making in the scheduling management of prefabrication construction. This research is expected to be further improved by incorporating broader data sources and including more delay factors in future research.

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