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Research on the Mechanism of Safety Risk Influencing Factors in the Construction of Prefabricated Building

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Abstract:

In order to scientifically study the construction safety risk transmission mechanism of prefabricated building, reduce the incidence of construction safety accidents and control key risk factors; a safety risk mechanism model combining the adversarial interpretive modeling ISM and MICMAC method is proposed to deal with the construction risks of prefabricated building. By analyzing the construction characteristics of prefabricated building, studying the risk sources and reading a large amount of literature, the construction safety risk influencing factor system is summarized. Based on the AISM method, a complex relationship analysis of risk indicators is conducted, a multi-level recursive structure model is formed, and the MICMAC method is applied to identify the high kinetic and high dependent factors of construction safety risks. The results show that workers' safety awareness and safety protection ability are the two most important direct causes triggering construction safety risks; construction scheme design is the most relevant factor in the system structure; reasonable construction schedule and management attention to safety issues are the deep root factors affecting construction safety risk management. All of these results give reference and guidance to construction risk management of prefabricated building.

***Keywords**: Prefabricated buildings, Construction risk, Structural interpretation modeling, MICMAC*

I. INTRODUCTION

In today's society, energy saving and environmental protection have become the mainstream concept, and prefabricated buildings are favored by the construction industry with the characteristics of "five savings and one environmental protection" [1]. At the same time, the sudden outbreak of Covid-19 epidemic has also verified the superiority of prefabricated building in rapid construction, so prefabricated building are bound to become the trend of future industry development. As we all know, the construction industry is a high-risk industry. The literature on traditional building construction safety risk research has been more mature. However the risk research system of prefabricated building, a product catalyzed by

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industrial development, has not been fully established in China, so it is necessary to study the mechanism of prefabricated building construction safety risk management. Through in-depth analysis of the correlation between the factors influencing the construction safety risk of prefabricated building, it is possible to identify the construction safety influencing factors in an organized and hierarchical manner and to lay the foundation for in-depth research on the construction safety risk of prefabricated building.

II. IDENTIFICATION OF FACTORS AFFECTING SAFETY RISKS IN THE CONSTRUCTION OF PREFABRICATED BUILDING

Construction safety risk identification methods in the traditional construction mode can be divided into two categories: empirical analysis method and systematic safety analysis method[2]. The empirical analysis method is a method to obtain risks by comparing safety technical specifications, safety operation procedures, safety management documents and practical experience of similar construction projects. It is applicable in new construction projects with experience of similar construction projects. System safety analysis method is a method to obtain the risk in the system by studying various factors in the system that may cause system insecurity and their interconnection, and the system safety analysis method is characterized by scientific method, comprehensive system, and strong theoretical property.

In this paper, for the construction process and flow of prefabricated building, the existing construction safety management standards, norms and related literature models at home and abroad are combined with national and local standards and norms related to the construction of prefabricated building to identify the factors influencing the safety of assembly building construction risks.

2.1 Standards and Norms Analysis

Construction safety management standards and codes at home and abroad are the summary and cream of years of experience in construction safety management, so the reading and sorting of codes is an effective way to obtain the factors influencing construction safety. This paper focuses on reviewing the main codes currently promulgated for construction safety management in China, and appropriately expands the scope by referring to the relevant regulations of countries and regions such as Hong Kong, Singapore and Japan, as shown in Table I.

TABLE I. Specifications of construction safety management in different countries or region

Country/Region	Document Name	Abbreviation
Mainland China	Standard for Safety Inspection of Building Construction (JGJ59-2011)	JGJ59
	Code for Safety Production Management of Construction Enterprises (GB50656-2011)	GB50656
	Regulations on Administration of Safety Production of Construction Projects	Ordinance
	Standard for Safety Production Evaluation of Construction Enterprises (JGJ/T77-2010)	JGJ/T77
Hong Kong,	Factories and Industria l Under takings Ordinance (FIUO-Cap.59)	FIUO

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China	Occupational Safety and Health Ordinance (OSHO-Cap.509)	OSHO
Japan	Construction Occupational Health and Safety Management System (COHSMS)	COHSMS
	Guidelines & COHSMS External System Evaluation	GCESE
Singapore	The Factories (Building Operations and Work of Engineering Construction) Regulations	BOWES
	Code of practice for safety management system for construction Worksites (SingaporestandardCP79:1999)	CP79

Although the norms of different countries and regions differ slightly in content and form, there are certain commonalities in safety management. In accordance with the principle of each code set as mandatory provisions and multiple codes of general concern, this paper summarizes the construction safety impact elements that are of key concern after studying the relevant specifications, as shown in Table II.

Table II. Factors affecting safety risk in different specifications

Influencing factors	Source
Design of construction scheme	JGJ59, Regulations, GB50656, GB50715
Safety management organization	Regulations, GB50715, GB50656, FIUO, COHSMS, BOWES Regulation, CP79
Safety education and training	GJ59, Regulations, GB50656, FIUO, CP79
Safety inspection	GJ59, Regulations, GB50656, FIUO, CP79
Site safety environment	GJ59, Regulations, GB50715, CP79
Safety technical disclosure	JGJ59, Regulations, GB50656, FIUO
Safety protection equipment	GB50656, CP79
Handling of safety accidents	GJ59, Regulations, FIUO, COHSMS, CP79
Emergency rescue plan	JGJ59, Regulations, GB50656, FIUO, COHSMS, CP79

2.2 Literature Analysis

The academic circle has carried out extensive research on construction safety management. Matthew finds that the actions of non-safe workers have a serious and far-reaching impact on construction barriers. After an analytical study of the construction workers safety awareness, his finding yields criteria for the construction workers to prevent safety accidents and avoid safety risks[3]. Tamoaitiene pointed out that in the construction process of prefabricated residential buildings the adoption of risk monitoring system and reasonable risk management plan can timely detect potential risks and reduce the probability of risk accidents[4]. Based on the literature review of construction safety, through the in-depth analysis of the relevant literature on the construction safety factors of prefabricated buildings, the influential factors which are generally considered as important in most studies are extracted, as shown in Table III.

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Table III. Factors affecting safety risk in literature analysis

Factors	Source
Safety awareness of management	Aksom and Hadikusum[5], Lee and Jaafar[6]
Safety input	Chang Chunguang[7], Tam et al[8], Fang et a[9]
Rationality of modular design	Moon et al[10], Stamatiadis et al[11]
Rationality of construction progress	Zhang and Thai[12]
Safety atmosphere	Hallowell et a[l13],Li et al[14]
Safety meeting	Lee and Jaaf[6],Cheng et al[15], Fang et al[9]
Safety awareness of workers	Yu et a[16], Tarek et al[17]
Worker safety protection ability	Khan et al[18], Pinto[19]

Through the above two methods, the influencing factors of construction safety management from the construction safety management standards and specifications and literature analysis are summarized, as shown in Table IV.

Table IV. Summary of factors influencing in construction of prefabricated building

Number	Factors	Source
1	Rationality of modular design	Moon et al[10], Stamatiadis et al[11]
2	Design of construction scheme	JGJ59, Regulations, GB50656, GB50715
3	Safety input	Chang Chunguang[[7], Tam et al[8], Fang et a[9]
4	Safety education and training	GJ59, Regulations, GB50656, FIUO, CP79
5	Safety meeting	Lee and Jaaf[6], Cheng et al[15], Fang et al[9]
6	Safety inspection	GJ59, Regulations, GB50656, FIUO, CP79
7	Rationality of construction progress	Zhang and Thai[12]
8	Site safety environment	GJ59, Regulations, GB50715, CP79
9	Safety atmosphere	Hallowell et a[l13], Li et al[14]
10	Safety technical disclosure	JGJ59, Regulations, GB50656, FIUO
11	Safety protection equipment	GB50656, CP79
12	Safety awareness of workers	Yu et a[16], Tarek et al[17]
13	Worker safety protection ability	Khan et al[18], Pinto[19]
14	Handling of safety accidents	GJ59, Regulations, FIUO, COHSMS, CP79
15	Safety awareness of management	Aksom and Hadikusum[5], Lee and Jaafar[6]
16	Safety management organization	Regulations, GB50715, GB50656, FIUO, COHSMS, BOWES Regulation, CP79
17	Emergency rescue plan	JGJ59, Regulations, GB50656, FIUO, COHSMS, CP79

III. FUNDAMENTALS OF THE CROSS IMPACT MATRIX MULTIPLICATION APPLIED TO CLASSIFICATION WITH THE ADVERSARIAL INTERPRETIVE STRUCTURE MODELING

The interpretive structure modeling (ISM) was proposed by Warfield in 1973 [20]. It is mainly used to analyze the constituent elements of complex systems and their interdependencies and inter-constraint relationships. Its basic principle is to decompose the constituent elements of a complex system into several

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subelements; after a series of topological operations, a single hierarchical diagram is derived in a result-oriented manner; and the hierarchical diagram is arranged into a multi-level recursive mechanism from top to bottom, i.e., a cause-effect reachable sequence is derived by the way of finding effects through cause, which is expressed in a hierarchical directed topological diagram [21]. While Adversarial Interpretive Structure Modeling Method (AISM) is a new approach derived from the interpretive structure modeling in recent years [22]. The main core method is to introduce the game adversarial on top of the ISM result-oriented hierarchical ranking rules, add the cause oriented ranking rules that are opposed to the ISM ranking rules, and place the elements from the bottom to the top, i.e., the cause-effect reachable sequences are sought by the way of finding the cause through effect, so as to build a set of directed topological graphs that are opposed to the ISM ranking rules.

The process of AISM can be described as shown in Figure 1.

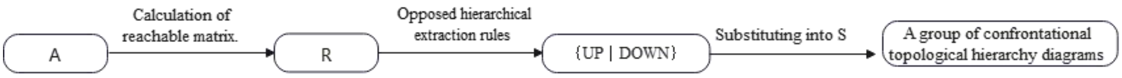

Fig 1: the process of AISM

Where, A is the relationship matrix of Boolean type; R is the reachable matrix; is the general skeleton matrix; UP type topological hierarchy diagram and DOWN type topological hierarchy diagram are a set of adversarial hierarchy diagrams.

Cross Impact Matrix Multiplication Applied to Classification (MICMAC) analysis is a method of classifying elements in a system using cross-influence matrix multiplication [23]. It is generally used for problems such as analyzing the importance of elements in a system in complex environments and matching the corresponding solutions.

ISM identifies the influencing factors of the system through various methods, techniques and tools; analyzes the linkages between elements or factors and draws directed diagrams; decomposes the fragmented, irregular and complex relationships between factors into clear multi-level recursive structural models through matrix models after regionalization and hierarchical leveling to improve the level of knowledge and understanding of the problem. MICMAC is used to identify the system with highly dynamic and highly dependent factors in the system. Since both methods start from the system analysis of factor relationships and the final reachable matrix of ISM is the same as the stable indirect matrix in MICMAC. Therefore, many scholars have used the two analysis methods together and achieved desirable results. Khan and Haleem apply the fuzzy MICMAC model and ISM analysis to find out the key motivating factors for organizations to make intelligent transformation[18]. DVivek et al. applies ISM and MICMAC to find the influencing factors that enable firms to stand out among their peer group companies. Zhao Huiru et al. apply ISM and MICMAC to analyze the operational early warning indicators of power grid companies to identify the key factors in their operational management[24].

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In general, ISM and MICMAC are used to analyze the interrelationship process of the influencing factors in the system as shown in Figure 2.

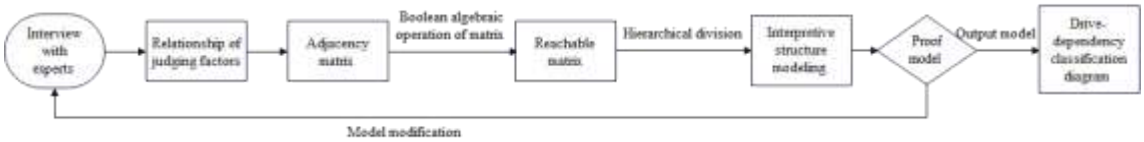

Fig 2: flowchart of integrated method synthetizing AISM and MICMAC

IV. ANALYSIS OF CONSTRUCTION SAFETY RISK IMPACT FACTORS BASED ON AISM AND MICMAC

4.1 Acquisition of basic data

For the 17 prefabricated building construction safety risk influencing factors identified above, the relationships among the influencing factors are further identified to clarify their mechanisms of action in the safety management of prefabricated building construction. The relationship between the identified factors can be obtained through questionnaire surveys or expert interviews, and since the relationship between the influencing factors of safety risks in prefabricated building construction is a subjective perception, the data obtained through expert interviews are more accurate than questionnaire surveys. Therefore, this paper adopts the expert interview method to clarify the influence relationship between the influencing factors. The team goes to each prefabricated project team during 2021 to conduct in-depth communication with 15 experienced experts, 6 of whom are from universities and 9 are from construction and supervision companies engaged in prefabricated projects, as detailed in the table. The rich experience of the experts lays a reliable foundation for determining the relationship between the factors influencing safety risks in the construction of prefabricated buildings.

After the interview to obtain the direct influence relationship between the factors, 15 experts individually judge the relationship between the influencing factors according to the following rules: if the factor F_i has impact on $F_j, a_{ij}=1$; if there is no impact between them, $a_{ij}=0$; if the factor F_i and F_j influence each other and have the same influence, $a_{ij}=a_{ji}=1$; if the influence is not the same, the more influential factor takes the value of 1 and the smaller one takes the value of 0. According to the results of expert judgment, by the formula to determine the relationship between factors, if there are 10 and more experts think that the construction safety risk impact factor F_i has a direct impact on F_j, then $a_{ij}=1$; if less than 5 and below experts think that the construction safety risk impact factor F_i has a direct impact on , $F_j, a_{ij}=0$, and finally a total of direct action relationships on factors are determined.

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$$a_{ij}=\begin{cases}1 \ More\ than\ 67\%\ of\ experts\ believe\ that\ the\ influence\ factor\ F_i\ has\ a\ direct\ impact\ on\ F_j\\ 0 \ \ Less\ than\ 33\%\ of\ experts\ believe\ that\ the\ influence\ factor\ F_i\ has\ a\ direct\ effecton\ F_j\end{cases}$$

Based on the final discussion results of the expert interviews, the adjacency matrix is created.

4.2 AISM model of the factors influencing safety risks in prefabricated construction

Taking the factors influencing the safety risk of prefabricated construction as nodes and the relationship between factors as directed edges, the adjacency matrix can be more graphically represented as Figure 3 according to the interrelationship between factors in the adjacency matrix.

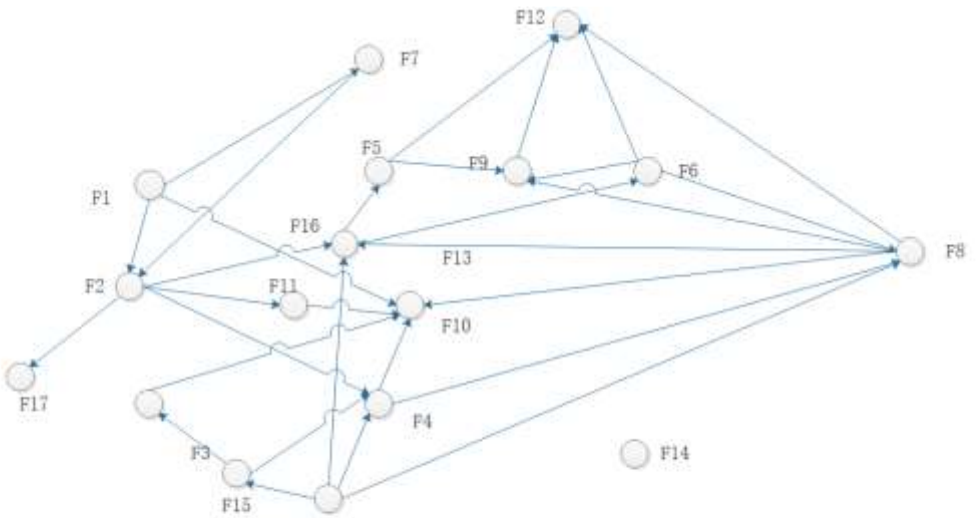

Fig. 3: directional diagram of factors influencing construction safety risks

As can be seen from the figure, there are 31 pairs of influence relationships among the 17 influencing factors; safety accident handling (F14) is completely independent, i.e., there is no connection between the relevance of safety accident handling and other influencing factors; construction program design rationality (F2) establishes the most direct connections with other factors, and the scope of influence factors is more extensive. However, there are some fundamental influencing factors that are extremely important for the construction of prefabricated buildings, although their direct scope of action is limited, and the importance of such influencing factors at the bottom level for the safety of prefabricated building construction is not reflected in the figure.

Based on the established adjacency matrix, the adjacency multiplication matrix is calculated and shown in Table V.

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Table V. Adjacent multiplication matrix of construction safety influence factors

Table	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F1	1	1					1						1				
F2		1		1						1						1	1
F3			1	1							1						
F4				1				1					1				
F5					1				1			1					
F6						1		1	1			1					
F7		1					1										
F8								1	1			1	1			1	
F9									1			1					
F10										1			1				
F11											1		1				
F12												1					
F13													1				
F14														1			
F15			1	1				1							1	1	
F16					1	1										1	
F17																	1

The reachable matrix of safety influencing factors of prefabricated building construction is obtained by adding the unit matrix I to the adjacency matrix A to obtain the matrix (A+I), i.e., a Boolean square matrix with only diagonal 1. After the Boolean algebraic algorithm to multiply B successively, until so that all products after the kth power (including the kth power) are equal, and then the product is the requested reachable matrix.

From the reachable matrix R for point reduction, get the reachable matrix R′ ; carry out the edge reduction operation to get the skeleton matrix; and then substitute loop element to get S, that is, the general skeleton matrix, the flow chart is shown in Figure 4.

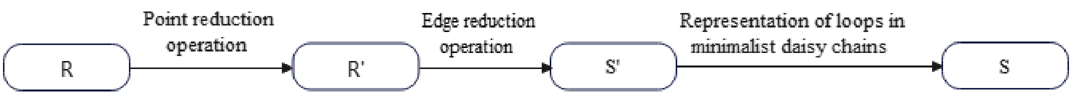

Fig 4: Calculation flow chart

Based on the reachable matrix, the reachable set, prior set and common set between each factor are summarized. Then the decomposition is carried out according to the relevant principles. According to the extraction rules, after extracting the UP-type and DOWN-type topological layers step by step respectively, the results of adversarial layer extraction can be obtained, as shown in Table VI.

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Table VI. Adversarial hierarchy extraction results

Hierarchy	Result Priority – UP Type	Cause Priority-DOWN Type
Layer 0	F12, F13, F14, F17	F12
Level 1	F9, F10, F11	F9
Layer 2	F5	F5, F13
Layer 3	F6, F8, F16	F6, F8, F16
Layer 4	F4	F4, F10, F17
Level 5	F2, F3	F2, F11
Layer 6	F7, F15	F3, F7
Level 7	F1	F1, F14, F15

According to the relationship between elements and the result of confrontation hierarchy extraction, the directed topological hierarchy diagram can be drawn. The reachable relationship between prefabricated construction safety influence factors is represented by directed line segments. UP type directed topological hierarchy diagram and DOWN type directed topological hierarchy diagram are shown in Figure 5. The two-way arrows in the diagram indicate the formation of a circuit, i.e. mutual reachable relationship, while the lower layer indicates that the influence factors have root cause and the upper layer indicates that the influence factors have directness.

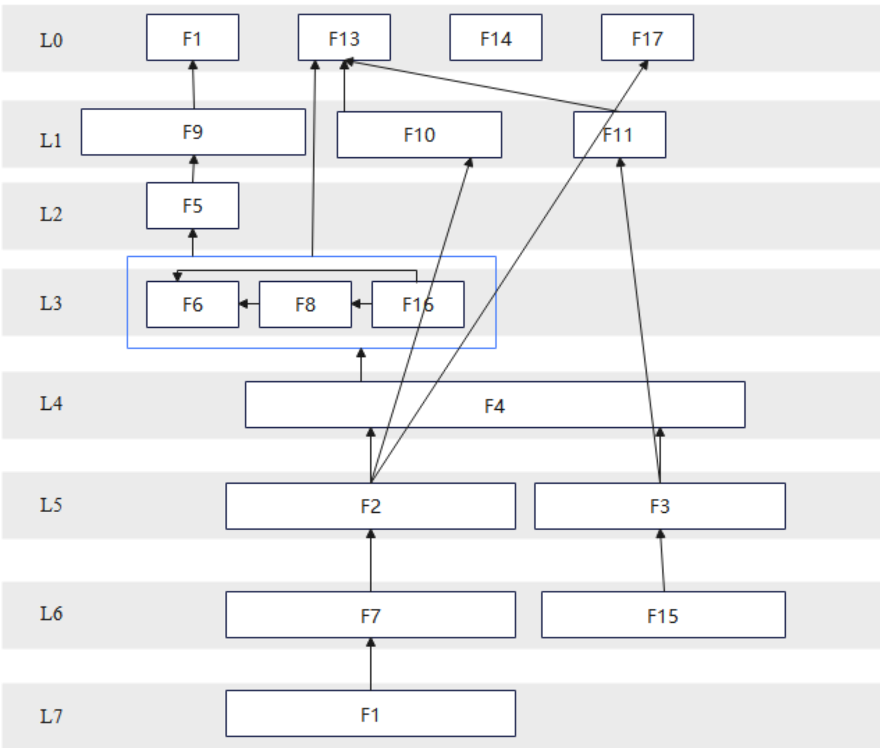

Fig. 5: ASIM mechanism model of safety risk in construction of prefabricated building

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4.3 MICMAC Classification Chart of Safety Risk Influencing Factors of Prefabricated Construction

From the final reachable matrix R, the driving power and dependencies of each influence are calculated according to Equation (1) and (2), as shown in Table VII.

$$D_i = \sum_{j=1}^{n} a_{ij} (i = 1, 2, \cdots, \ n) \tag{1}$$

$$R_i = \sum_{j=1}^{n} a_{ij} (i = 1, 2, \cdots, \ n) \tag{2}$$

Table VII. Value of driving power and dependence of metro construction safety factors

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
Dependency	1	3	2	6	10	9	2	9	11	4	3	12	12	1	1	9	4
Driving power	13	11	10	8	3	7	12	7	2	2	2	1	1	1	11	7	1

According to the driving power and dependency degree of each factor in the table, the driving power-dependency degree classification chart of safety risk impact factors can be drawn as shown in the figure 6. Construction safety risk impact factors can be classified into four clusters: I autonomous factors, II dependent factors, III linkage factors and IV independent factors. From the figure, it can be found that the most construction safety impact factors belong to autonomous factors, followed by independent factors, the least dependent factors, and no linkage factors. This indicates to some extent that the degree of association between the influencing factors is weak, and it is not possible to start from a single or a few construction safety influencing factors to achieve the control of all influencing factors by controlling a few influencing factors to achieve the purpose of improving safety management performance.

Autonomous factors include design program constructability (F4), safety meeting (F8), safety inspection (F9), safety atmosphere (F12), safety technical delivery (F13), safety protective equipment (F14), safety accident handling (F17), safety management organization (F19) and emergency rescue plan (F20). They are relatively independent of other factors and therefore not easily influenced by other factors. Dependent factors include safety education and training (F7), site safety environment (F11), workers' safety awareness (F15), and workers' safety protection ability (F16), among which F15 and F16 are at the uppermost level of the interpretive structure modeling and are the most directly influencing factors of construction safety risk. The independent factors are mainly construction plan design (F5), investment in safety cost (F6), reasonable construction schedule (F10) and management attention to safety (F18), which is usually at the lowest level of the interpretive structure modeling and are the most fundamental factors

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influencing construction safety. Therefore, sufficient attention needs to be paid to these factors in safety management activities.

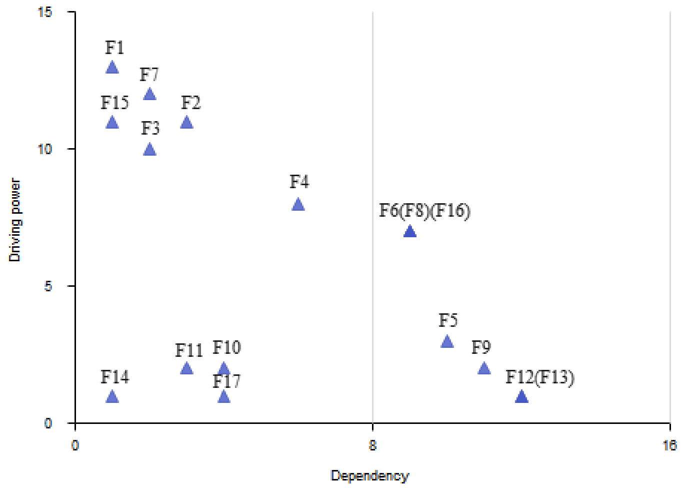

Fig 6: driving-dependence classification plot construction safety factors

III. CONCLUSION

Using AISM model and MICMAC method can hierarchize and organize the relationship of safety risk influencing factors of prefabricated building construction, and the following analysis results are obtained:

From the figure, we can see that the hierarchical model of construction safety risk influencing factors shows asymmetry, and workers' safety awareness (F15) and safety protection capability (F16) are located in the superficial layer of the AISM model, which is in the high-dependency, low-drive dependency cluster in the MICMAC matrix. Therefore, workers' safety awareness (F15) and safety protection capability (F16) are the two most important direct causes of triggering construction safety risks and are influenced by several subordinate factors, and other factors mainly trigger construction safety accidents by influencing these two factors. Safety incident handling (F17) does not change its independent properties through matrix operations, and F17 is not linked to other factors.

In the middle layer, the construction plan design (F5) is the most relevant factor in the system structure, which is influenced by the reasonable construction schedule (F10), directly affects factors such as safety education and training (F7), safety technical delivery (F13) and emergency rescue plan (F20), and indirectly affects the site safety environment (F11), workers' safety awareness (F15) and safety protection capability (F16) and other factors, and are in a high-driven, low-dependency independent cluster in the MICMAC matrix. Therefore, developing a reasonable construction plan design is an important measure and an effective way to reduce safety risks. Secondly, the site safety environment (F11) also has a strong correlation, but is in a high-dependency, low-dependency dependency cluster in the MICMAC matrix.

The ISM structural model shows that reasonable construction schedule (F10) and management attention to safety issues (F18) are located at the 5th level of the structural model, indicating that these factors are the deep root factors influencing construction safety risk management. In the MICMAC matrix, these 5 factors are in independent clusters with high drivers and low dependencies, indicating that these factors have a high degree of influence on other factors and a weak degree of influence by other factors. Therefore, determining a reasonable construction schedule is an important guarantee to ensure the safety of prefabricated building construction. In addition, management's emphasis on safety (F18) will have an impact on the investment of safety costs (F6), safety inspection (F9) and safety management organization (F19), which will motivate the management organization to work hard and is a root organizational factor to reduce construction safety accidents.

Through the above analysis, the factor which has the strongest correlation with the construction scheme design can be found. Therefore, the pre-control of safety risks in the pre-construction stage is an effective way and key link to reduce safety accidents in the construction of prefabricated buildings.

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