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CONSTRUCTION MANAGEMENT

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Investigating the impediments to carbon emission mitigation in prefabricated construction: a stakeholder perspective

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ABSTRACT

Prefabricated construction is a promising global technology for reducing carbon emissions (CEs) in the construction sector. This study aims to identify critical factors affecting the life cycle of prefabricated buildings, understand their interrelationships, and develop targeted carbon reduction measures. A mixed-methods approach is employed, incorporating bibliometric analysis to identify key factors and the Delphi method to refine these factors through iterative surveys with diverse stakeholders. A 24-member scoring panel and a 3-member review panel consisting of experienced corporate practitioners were selected for the study. The DEMATEL-ISM approach was utilized to analyze causal and hierarchical relationships, revealing both direct and indirect impacts on CEs. The findings indicate that factors such as energy efficiency and behavior change significantly affect CEs in prefabricated buildings. The study categorizes 15 key factors, including energy efficiency, environmental properties, behavioral change, and water and solid waste management. Furthermore, it underscores the importance of building design, energy-saving awareness and habits, and policies and regulations in reducing carbon emissions in prefabricated construction. These insights are valuable for advancing sustainable building research, analyzing stakeholder attitudes, and informing engineering project studies.

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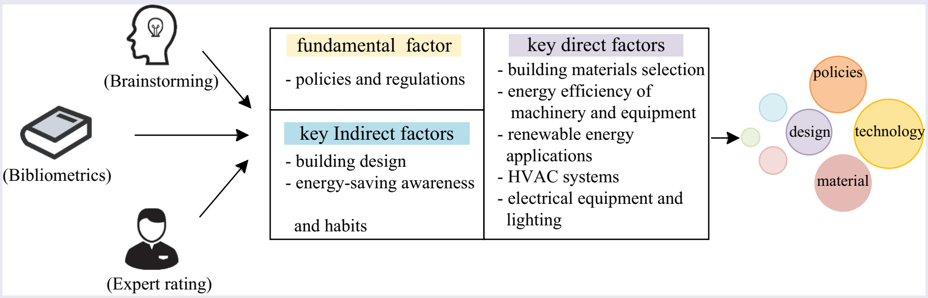
Prefabricated construction; influencing factor; stakeholder; carbon reduction; DEMATEL-ISM



1. Introduction

Prefabrication is a widely recognized construction technology that can reduce carbon emissions (CEs) (Hao et al. 2020). China's *14th Five-Year Plan for the Construction Industry* aims to increase the proportion of assembled buildings in new buildings to over 30% by 2025 (Li et al. 2021; Ministry of Housing and Urban Rural Development 2022). China's "dual-carbon" strategy focuses on carbon reduction in the construction sector, aiming for carbon neutrality. Although assembled buildings are greener and lower carbon than traditional cast-in-place buildings, they still have significant potential to reduce emissions (Wang et al. 2023).

The industrialization of assembled buildings has led to significant differences in production, cost, management, and other aspects compared to traditional concrete buildings. Research has focused on the environmental impacts of assembled buildings, including ecological damage, construction waste, and CE. The Construction Environmental Performance Assessment System (CEPAS) and Building Health Impact Assessment System (BHIAS), for instance, were developed to measure the ecosystem damage, resource depletion, and health damage of assembled buildings compared to traditional cast-in-place buildings (Cao et al. 2015). The results show that assembled buildings significantly reduce resource depletion.

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Ferdous et al. (2019) research into assembled buildings found that construction processes contribute to 32% energy consumption, 30% CO_2 emissions, and 30–40% waste generation. Dong and Ng's (2015) study of a Hong Kong residential house found that assembled buildings can reduce CE by 10% per cubic meter, compared to traditional cast-in-place methods.

The emission reduction potential of assembled buildings varies significantly from study to study, making it challenging to apply results to other programs. Therefore, it is more practical to study key factors affecting this potential and formulate emission reduction measures based on these factors. Scholars have identified these factors from various research perspectives (Wang et al. 2022; Zhang et al. 2022), but most are not isolated and have different relationships with each other (Ding, Xu, and Wang 2023). A clear analysis of these influencing factors and their complex interactions can help stakeholders in the (prefabricated) assembly building sector make more low-carbon and environmentally friendly decisions. Previous studies of CE from assembly buildings have analyzed factors such as building structure, materials, transportation distances, and construction methods at a micro level (Hong et al. 2015). Macro-level factors such as social development, economic demographics, government decision-making, market environment, and energy consumption have also been investigated (Liu et al. 2015).

This study investigates the influencing factors of CE in assembled buildings at both macro and micro levels, incorporating supply chain stakeholder analysis and considering factors like behavioral patterns, energy systems, environmental impacts, material selection, and equipment operation. Using bibliometric and Delphi methods, combined with the DEMATEL-ISM method, the study identifies key influencing factors and their relationships. Based on assembly supply chain stakeholders, the study explores effective measures to reduce CE. The theoretical framework applies to analyzing CE in assembled buildings and engineering projects in other fields.

2. Previous research into carbon emissions from assembled buildings

The study of CEs in construction has become a significant research area, with studies focusing on factors influencing CE in the macro industry (Qi and Zhang 2013), prediction (Pu et al. 2022), efficiency (Hui and Su 2018), measurement, and emission reduction measures (Ding et al. 2020). The field is expanding to include CE accounting (Gao et al. 2023), energy efficiency (Li and Colombier 2009), low-carbon materials (Orsini and Marrone 2019), and renewable energy (Ahmed et al. 2022).

Based on previous studies, several scholars have addressed the factors influencing carbon emissions from assembly buildings. (Lu et al. 2019, 2021; Sandanayake, Luo, and Zhang 2019) quantified the direct and indirect carbon emissions during the building fabrication phase of assembly buildings and compared them with traditional cast-in-place buildings to identify technological, managerial, and policy factors. Luna Tintos et al. (2020) suggested that advanced technology, personnel management and energy structure optimisation to achieve low carbon in assembled buildings. Xue et al. (2018) pointed out that technological upgrades and increased economic inputs are the key to achieving green and low carbon buildings through their study of building stakeholders. Zhu et al. (2022) identified five dimensions of carbon emission reduction influence and through their study found that the management model has the strongest influence on carbon emission reduction factors, followed by government policies, technological level and economic inputs, and energy structure had the weakest influence. Greer (2023) confirmed through a case study that most modular types can reduce emissions by 2%-22% compared to conventionally built housing units, with the potential benefits depending on the structural framing material and factory location. Karlsson et al. (2021) analysed the actual level of emission reductions of different building designs and different emission reduction measures from a supply chain perspective, explored the potential of combining existing technologies with emission reduction measures to reduce carbon emissions, and concluded that increasing the recycling rate of materials is worthwhile. Xu et al. (2020) also demonstrated in a case study that sustainable material applications can be effective in reducing carbon emissions.

In summary, existing research has thoroughly examined the carbon reduction potential of prefabricated buildings from various perspectives, including technology, management, energy structure, policy, and economics. The carbon emissions of different projects are influenced by a multitude of factors, with the degree of influence varying depending on the specific circumstances of each project. Despite this, significant knowledge gaps remain in the comprehensive analysis of the factors affecting prefabricated buildings. In the current research on carbon emissions from prefabricated buildings, although the independent analyses of each factor have reached a certain depth, these factors are often related to each other and have complex interaction effects on the overall carbon emissions. Therefore, it is crucial to construct a comprehensive and systematic analysis framework, which can not only effectively integrate the influencing factors and reveal the mechanism of their interactions, but also provide theoretical support for the formulation of more scientific and reasonable emission reduction strategies, so as to enhance the overall explanatory power and application value of the research results.

In this paper, we develop an overarching framework based on the perspective of the prefabricated building supply chain. In practical application, decision-makers of prefabricated building projects can use this analytical framework to engage different stakeholders in decision-making processes, taking into account local policies, geographic conditions, technological levels, and personnel quality. This approach aims to identify the most effective carbon reduction measures tailored to the specific engineering conditions and policy contexts of each project. This methodology contrasts with the practice of indiscriminately selecting carbon reduction measures based on previous studies, emphasizing the importance of project-specific conditions and policy contexts.

3. Method

A multi-step methodology is used as follows:

3.1. Stakeholder analysis

The study initiated with an assembly building stakeholder analysis to identify a range of experts. Two groups of experts were selected based on their relevance to the field.

3.2. Literature search and delphi method

The bibliometric method allows for the systematic sorting and quantification of key factors in existing research, ensuring that the factors selected are supported by broad academic consensus and data. The Delphi method, on the other hand, further validates and refines these factors through multiple rounds of expert consultation to ensure that they are in line with the current research context and practice needs. The combination of the two not only enhances the objectivity and comprehensiveness of factor selection, but also increases the scientific and applied value of the research results. The first group of experts participated in a literature search and Delphi method to identify the initial influencing factors. This process involved iterative surveys to achieve a consensus among experts regarding the key factors.

3.3. DEMATEL method

The identified factors were subjected to the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. This involved dividing the factors into regions and extracting those with a significant impact on CEs in assembly buildings. Analysing the influencing factors using the DEMATEL method can effectively reveal the interrelationships and causal chains among the factors and clarify which factors are key drivers and which are passive influences. Through this method of analysis, the complex interactions within the system can be understood in depth, thus providing a scientific basis for the formulation of more precise and targeted strategies and enhancing the rationality and effectiveness of the decision-making process. The Triangular Fuzzy Number (TFN) was used for fuzzy quantification, allowing for an objective evaluation of factors while eliminating subjective influences from expert scores.

3.4. Validation and Re-analysis

The results of the DEMATEL analysis were validated with a second group of experts. If significant deviations were observed, the researchers communicated these to the experts, collected feedback, and organized responses for re-analysis.

3.5. ISM method

Analysing factors using Interpretative Structural Modelling (ISM) helps to systematically stratify and sort out the hierarchical relationships between influencing factors, and clarify the position and role of each factor in the overall system. By constructing a structured model of the factors, ISM can reveal the logical relationship between the underlying driving factors and the surface influencing factors, thus providing theoretical support for the decomposition of complex problems and the determination of solution paths, and enhancing the systematic and hierarchical nature of the research. Based on the DEMATEL results, thresholds were calculated, and the Interpretive Structural Modeling (ISM) method was applied to map hierarchical relationships among the identified important factors.

3.6. Combination of results

The findings from the DEMATEL and ISM analyses were combined to derive the key influencing factors involved.

3.7. Sensitivity analysis and stakeholder variability

The study incorporated sensitivity analysis by changing expert weights and analyzed stakeholder variability to assess the robustness of the results.

Figure 1 shows the research framework, outlining the sequential steps taken in the model building and analysis process, emphasizing a systematic and comprehensive approach to understanding the key influencing factors of CEs in assembly buildings.

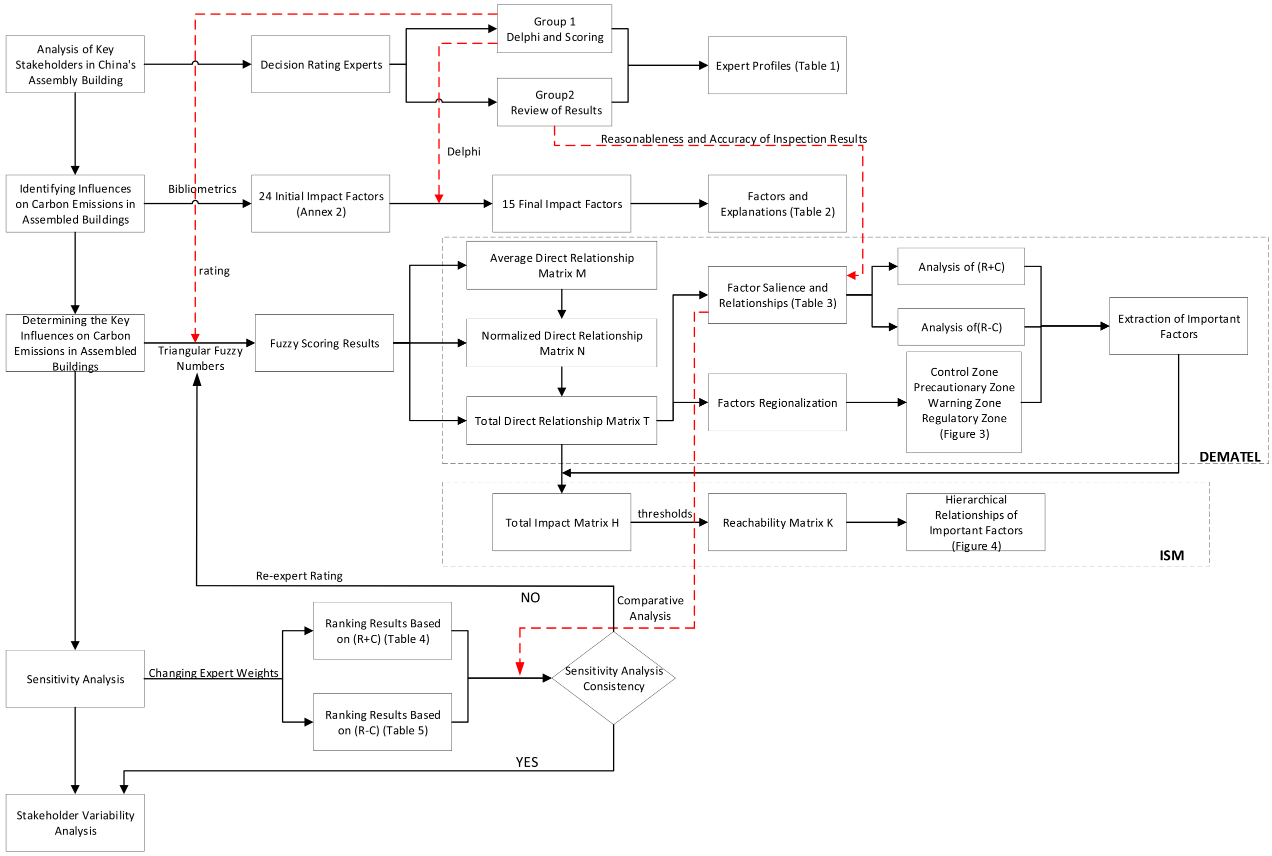

Figure 1. Research framework.

4. Analysis

4.1. Analysis of major stakeholders in China's assembled buildings

Due to the differences between an assembly building project and a traditional project, the stakeholders in an assembly building project differ from those in a traditional on-site construction project. The construction unit is the ultimate owner of the project, and they determine the project's needs, budget, and schedule. During the design phase, designers among the stakeholders need to be more proactive as experienced coordinators and interdisciplinary designers by coordinating and balancing the expectations and concerns of the different participants. In addition, design professionals should be able to design for manufacturability, constructability, and sustainability. Prefabrication plants produce the modules and components required for assembly buildings. During the manufacturing phase of precast production, design and construction personnel should align their terminology and processes with those of the manufacturer. The builder also needs to liaise closely with the design organization and the precast plant to ensure that the components are assembled and installed correctly to ensure the quality and safety of the project. Supervisory teams oversee the construction process to ensure compliance and quality. Consulting teams may include project management, cost management, and sustainability experts. They work with construction, design, and other stakeholders to ensure the successful completion of the project (Jiang et al. 2019; Kumar, Rangan, and Rufín 2005). Figure 2 shows the stakeholder interrelationships.

Considering that the assessment results of the two main bodies, the transportation unit, and the public, were somewhat inadequate at the academic level, we invited six units – including the construction unit, the design unit, the prefabricated components factory, the builder, the supervisory unit, and the consulting unit – with four experts from each of these units, to form a team of a total of 24 experts. Meanwhile, to test the research results' accuracy, we also invited three experts. Table 1 shows the information of the two groups of experts.

4.2. Identification of factors affecting carbon emissions from assembled buildings

Through a detailed literature review of related articles in the CNKI and Web of Science databases, 24 factors affecting CEs of assembled buildings were initially selected (Appendix 2). The purpose of this study and the description of the factors were sent to the experts in the first group using a questionnaire (Table 1), and they were asked to provide suggestions and opinions as to whether the selection and categorization of the

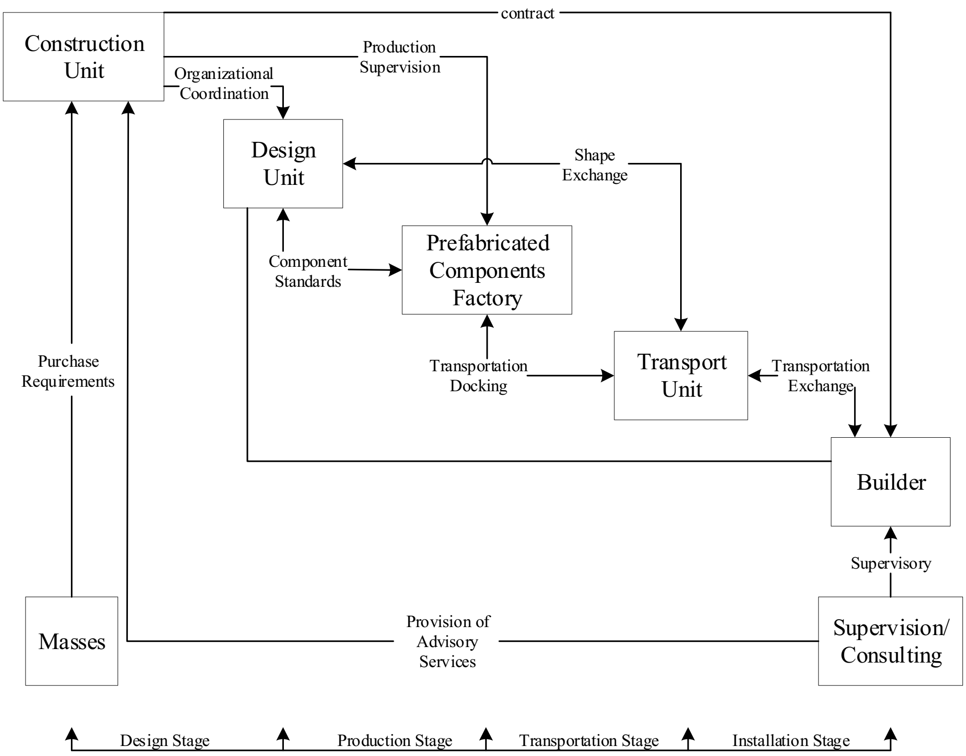

Figure 2. Relationships among key stakeholders in China's assembled buildings.

Table 1. Profiles of experts involved in this study.

Groups	Number of experts	City	Academia/manufacturing	Position	Experience (years)	Assembled building stakeholder segments
G1	4	Hefei, Anhui	Construction unit	Head of technology	10-15	Construction unit
	2	Hefei, Anhui	Design institute	Designer	10-15	Design unit
	1	Hefei, Anhui	Assembly research institute	Designer	20-25	
	1	Ningbo, Zhejiang	Design institute	Designer	5-10	
	1	Hefei, Anhui	Assembled components factory	Production manager	10-15	Assembled components factory
	1	Chuzhou, Anhui	Assembled components factory	Production manager	20-25	
	2	Hefei, Anhui	Assembled components factory	Head of department	10-15	
	2	Hefei, Anhui	Builder	Project manager	15-20	Builder
	1	Hefei, Anhui	Builder	Site manager	10-15	
	1	Wuxi, Jiangsu	Builder	Engineering manager	5-10	
	2	Hefei, Anhui	Supervision company	Project director	15-20	Supervisory
	2	Hefei, Anhui	Supervision company	Supervising engineer	5-10	
	1	Hefei, Anhui	Universities and colleges	Principal	25-30	Consulting
	3	Hefei, Anhui	Consultancy unit	Senior adviser	15-20	
G2	1	Hefei, Anhui	Universities and colleges	Associate professor	20-25	Consulting
	1	Hefei, Anhui	Builder	Project manager	15-20	Builder
	1	Hefei, Anhui	Construction unit	Head of technology	10-15	Construction unit

factors were reasonable and representative. The results of the first round of questionnaires were integrated and sent to the experts again. The experts reached satisfactory results on the selected influencing factors through three rounds of discussion. Finally, they identified 15 factors that impact the CEs of assembled buildings, as shown in Table 2.

4.3. *Key influencing factors*

4.3.1. *Scoring and fuzzy analysis*

The first group of experts was invited to rate Appendix 3, and the scoring rules are detailed in Table 1 of Appendix 1. Triangular fuzzy numbers are introduced, and the questionnaire results are fuzzy

Table 2. Influencing factors of CEs of assembled buildings and their interpretation.

Categorization	Serial number	Influencing factor	Description	Reference
Energy efficiency	X1	Building design	Building design encompasses material selection, energy efficiency, building shape and layout, etc. Rational building design can minimize CE from the building site and promote sustainable building development.	(Li & Lu, 2021; Du et al. 2021; Li, Chen, and Li 2022; Zhao, Sun, and Liu 2022)
	X2	Building material selection	Choosing low-carbon building materials for projects, such as renewable, recycled, and less energy-intensive materials, can help reduce a building's carbon footprint.	(Li and Lu 2021; Bouckaert et al. 2021; Du et al. 2021; Li, Chen, and Li 2022; Zhao, Sun, and Liu 2022)
	X3	Energy efficiency of machinery and equipment	Many different types of machinery and equipment are involved in the full life cycle of a building, and choosing clean energy and improving energy efficiency can effectively reduce the overall CE of a building.	(Ding, Xu, and Wang 2023)
	X4	Renewable energy applications	Utilizing renewable energy sources such as solar and wind to generate electricity or heat in buildings can significantly reduce reliance on traditional energy sources, reducing CE.	(Li and Lu 2021; Bouckaert et al. 2021; Li, Chen, and Li 2022)
	X5	Heating, ventilation, and air conditioning (HVAC) systems	Using efficient HVAC systems, such as ground source heat pumps and solar air conditioning, can reduce energy consumption and CE.	(Bouckaert et al. 2021; Zhao, Sun, and Liu 2022)
	X6	Electrical equipment and lighting	Choosing efficient electrical equipment and lighting systems, such as LED lighting and appliances with an A++ energy efficiency label, can reduce electricity consumption and CE.	(Bouckaert et al. 2021)
Environmental properties	X7	Greening and landscaping	Appropriate green design and landscape planning can provide better environmental performance, such as providing shade, lowering temperatures, reducing energy demand, and improving CE inside buildings.	(Liu et al. 2022)
	X8	Indoor environment optimization	Indoor environmental optimization refers to various design and engineering measures to provide a comfortable, healthy, efficient, safe, and sustainable indoor environment.	(Zhou et al. 2019)
Behavior change	X9	Energy-saving awareness and habits	The energy efficiency awareness and habits of the participants of the assembly building life cycle play a crucial role in reducing energy consumption and CE.	(Bouckaert et al. 2021)
	X10	Energy use monitoring and feedback	Energy use and monitoring systems allow managers and users to keep track of CE and energy consumption in real-time, contributing to better decision-making or influencing their behavior.	(Liu et al. 2020; Tao et al. 2018)
	X11	Policies and regulations	The formulation of relevant energy conservation policies and regulations by the government, such as mandatory energy consumption limits and emission standards, as well as incentives, will impact residents' energy use behavior.	(Li and Lu 2021; Bouckaert et al. 2021; Ding, Xu, and Wang 2023; Du et al. 2021; Li, Chen, and Li 2022; Zhao, Sun, and Liu 2022)
	X12	Carbon trading and carbon market	Carbon trading and carbon markets have been established in several regions and countries to enable businesses and building owners to buy and sell carbon allowances more cost-effectively, thereby stimulating the construction community to reduce CE.	(Ding, Xu, and Wang 2023; Zhao, Sun, and Liu 2022)
Water and solid waste management	X13	Water management	Reduce water and energy consumption, and thus CE, by adopting water-saving facilities and water management strategies.	(Li and Lu 2021)
	X14	Material recycling rate	Recycling waste building materials reduces the production of new materials and the CE associated with the production and transportation of new materials.	(Li and Lu 2021; Bouckaert et al. 2021; Du et al. 2021; Li, Chen, and Li 2022; Zhao, Sun, and Liu 2022)
	X15	Construction waste disposal methods	CE can be effectively reduced if reasonable recycling and reuse methods are adopted to convert waste into new building materials.	(Li and Lu 2021)

analyzed according to Equations 1-6 in Annex I to obtain the fuzzy exact values.

4.3.2. DEMATEL analysis

The average direct relationship matrix "M," the normalized direct relationship matrix "N," and the total direct relationship matrix "T" were created using the post-fuzzy data according to Equations 7-9 in Annex I. Table 3 shows the salience and relationships of the factors finally obtained.

The factor relationships and rankings in Table 3 were sent to the second group of experts to collect feedback and test the reasonableness and accuracy of the results.

(R+C) stands for "Reason + Caused," which is used to indicate that a factor is both a cause (R) and

Table 3. Salience and relationship of factors.

	R	C	R+C	R-C	(R+C) ordering	(R-C) ordering	Cause/effect
X1- Building design	4.313	4.132	8.445	0.181	3	2	Cause
X2- Building material selection	4.215	4.337	8.551	−0.122	1	10	Effect
X3- Energy efficiency of machinery and equipment	3.906	4.119	8.025	−0.213	7	14	Effect
X4- Renewable energy applications	4.077	4.128	8.205	−0.051	5	5	Effect
X5- Heating, ventilation, and air conditioning (HVAC) systems	4.059	4.161	8.220	−0.103	4	9	Effect
X6- Electrical equipment and lighting	3.932	4.001	7.932	−0.069	8	6	Effect
X7- Greening and landscaping	3.237	3.340	6.577	−0.103	15	8	Effect
X8- Indoor environment optimization	3.521	3.667	7.188	−0.146	13	11	Effect
X9- Energy-saving awareness and habits	4.118	3.994	8.113	0.124	6	3	Cause
X10- Energy use monitoring and feedback	3.748	3.755	7.503	−0.007	10	4	Effect
X11- Policies and regulations	4.831	3.672	8.503	1.159	2	1	Cause
X12- Carbon trading and carbon market	3.738	3.827	7.565	−0.089	9	7	Effect
X13- Water management	3.488	3.638	7.126	−0.151	14	12	Effect
X14- Material recycling rate	3.577	3.743	7.320	−0.166	12	13	Effect
X15- Construction waste disposal methods	3.587	3.833	7.420	−0.245	11	15	Effect

a consequence (C), which means that this factor affects and is affected by other factors at the same time.

According to Table 3, we exemplify that the top six factors are building materials selection (X2) > policies and regulations (X11) > building design (X1) > heating, ventilation, and air-conditioning (HVAC) systems (X5) > renewable energy applications (X4) > energy-saving awareness and habits (X9), which are indicator factors reflecting the fact that they have a very important place in the system and contribute to the changes in the CEs of assembled buildings which mainly involves two major aspects of energy efficiency and behavioral change. Firstly, in terms of energy efficiency, using energy-efficient building materials and equipment, such as insulation, energy-efficient light fixtures, and high-efficiency HVAC systems, can reduce the building's energy demand. In addition, integrating renewable energy systems, such as solar panels, wind turbines, and ground-source heat pumps, into the design can reduce a building's dependence on traditional energy sources. Secondly, in terms of behavioral change, the introduction of policies and regulations, as well as the emphasis on energy efficiency awareness, can encourage the assembly-building industry to adopt more sustainable practices.

Factors with (R-C) value greater than zero are called cause factors, which indicate that the factor easily influences other factors and affects the target subject in general; factors with (R-C) value less than zero are called result factors, which mean that the factor is easy to be influenced by other factors and disturb the system.

According to Table 3, we ranked the cause factors based on the values from the largest to smallest, and the ranking relationship is building design (X1) > policies and regulations (X11) > energy-saving awareness and habits (X9). We can find that the (R+C) values of these three factors are also higher, and they are in a prominent position in the CE research system of assembled buildings. This suggests that it is a relatively low-cost and sustainable approach for the government and related organizations to guide the low-carbon behaviors of enterprises through the establishment of industry standards, shape the environmental awareness and practices of the industry, and raise the energy-saving awareness of the whole society under the guidance of education and training. On the other hand, the top five factors, ranked in order of the absolute magnitude of the outcome factor values, are construction waste disposal methods (X15) > energy efficiency of machinery and equipment (X3) > material recycling rate (X14) > water management (X13) > indoor environmental optimization (X8). These factors relate to water and solid waste management and environmental performance and directly cause CE from assembled buildings. When CE changes, we can focus mainly on the changes in these factors to achieve the role of early warning.

4.3.3. Factor regionalization

Using the DEMATEL method, with the help of the average centrality value of 7.780, the factors are divided into four zones: control zone, precautionary zone, warning zone, and regulatory zone (Figure 3).

4.3.3.1. Region I – Carbon emission control zone.

Decisive forces are the factors that have a large influence on the whole system because of their large (R+C) and positive (R-C) values. All the factors within this region have a significant influence on other factors. In this study, three factors – policies and regulations (X11), building design (X1), and energy-saving awareness and habits (X9) – are located within this region.

4.3.3.2. Region II – Carbon precautionary zone.

Voluntariness is used to indicate initiative in a causality diagram. If a factor is considered active, it may be the cause of other factors. Factors within this zone belong to the lower (R+C) value, i.e., the factor may influence other factors in the system, but its influence is low and its role in influencing the whole system is small. Therefore, we do not need to spend too much time and energy paying attention to the factors in this region in the project. In this paper, there are no factors belonging to this region.

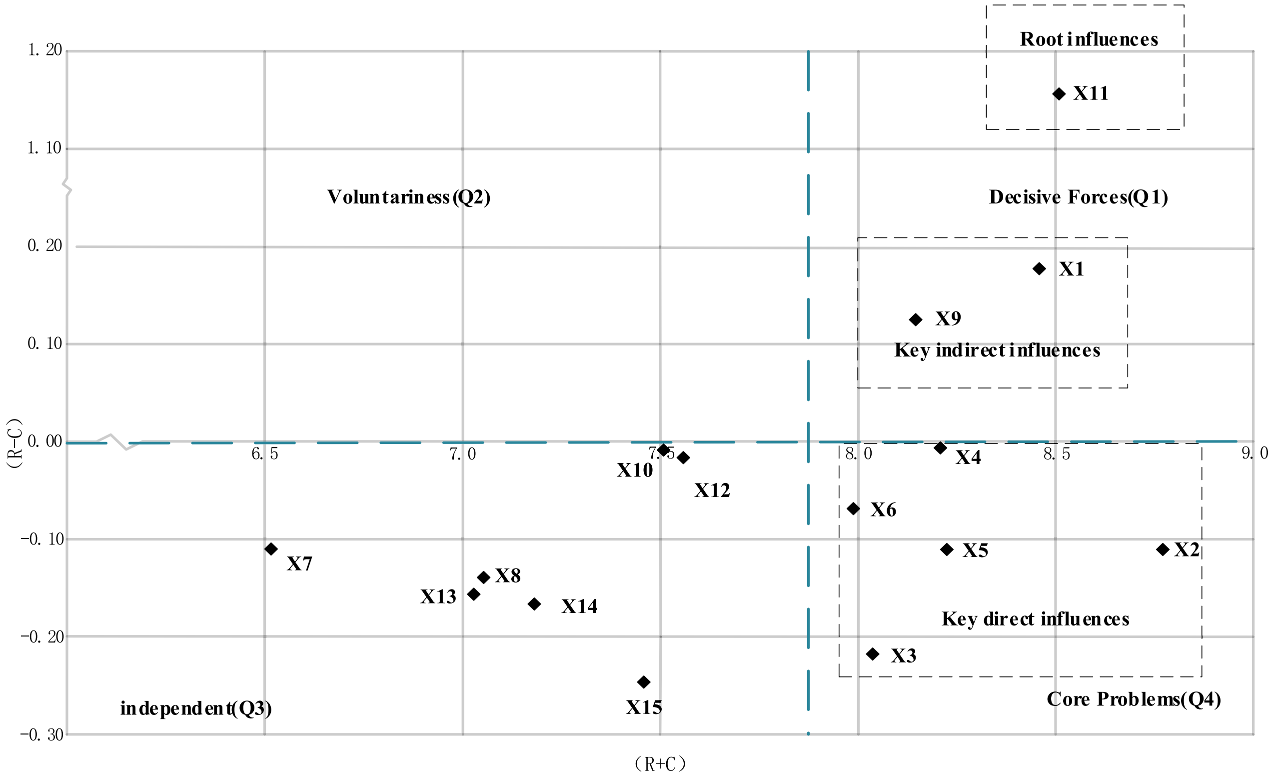

Figure 3. Factor salience.

4.3.3.3. Region III – Warning zone. Independent indicates the relative independence of the factors in the relationship diagram. The (R+C) value in the independence region is low, but the (R-C) value is negative and large in absolute value, so the factors in this region will not greatly impact the CE system of assembled buildings. However, they are susceptible to other factors so that we can regard the factors in the independence region as early warning factors. For example, suppose the recycling rate of materials is high. In that case, the building's detachability has been fully considered in the building design; the assembly rate is high, there are relevant standard constraints, and so on. On the contrary, if it is found that the recycling rate of materials is not high, then the relevant departments or decision makers should promptly look for the root causes of these problems and take timely measures to reduce the CEs of assembled buildings.

4.3.3.4. Region IV – Carbon regulatory zone. Core Problems are usually the main issues or focal points that need to be addressed. Factors with high (R+C) values in the outcome factors are included in this zone, including the five factors of building materials selection (X2); energy efficiency of machinery and equipment (X3); renewable energy applications (X4); heating, ventilation, and air-conditioning (HVAC) systems (X5); and electrical equipment and lighting (X6). These factors indicate a direct contribution to changes in CE from assembled buildings and are most susceptible to the influence of other factors. Therefore, the changes in these types of factors should be strictly monitored in CE control, not only to prevent the direct impact on CE from assembled buildings but also to pay attention to the impact of the changes in other factors on the factors in the region, to avoid the increase in CE indirectly caused by other factors.

4.3.4. Identification of key factors

After analyzing the characteristics of the four regions, eight factors that are more important to CE were initially extracted out of the 15 factors, including policies and regulations (X11); building design (X1); energy-saving awareness and habits (X9); building materials selection (X2); energy efficiency of machinery and equipment (X3); renewable energy applications (X4); heating, ventilating, and air conditioning (HVAC) systems (X5); and electricity equipment and lighting (X6).

In order to further study the important relationship between these factors, ISM analysis was performed on the above eight factors. The threshold $\lambda = 0.289$ was recalculated, and the final calculation results are shown in Figure 4. There are three tiers in total. The first tier has six factors, namely: building design (X1); building materials selection (X2); energy efficiency of machinery and equipment (X3); renewable energy applications (X4); heating, ventilation, and air-conditioning (HVAC) systems (X5); and electrical equipment and lighting (X6). The second tier of factors is energy-saving awareness and habits (X9). The third tier factors are policies and regulations (X11). Policy guidance can raise the awareness of carbon reduction among participants and users in the assembly building

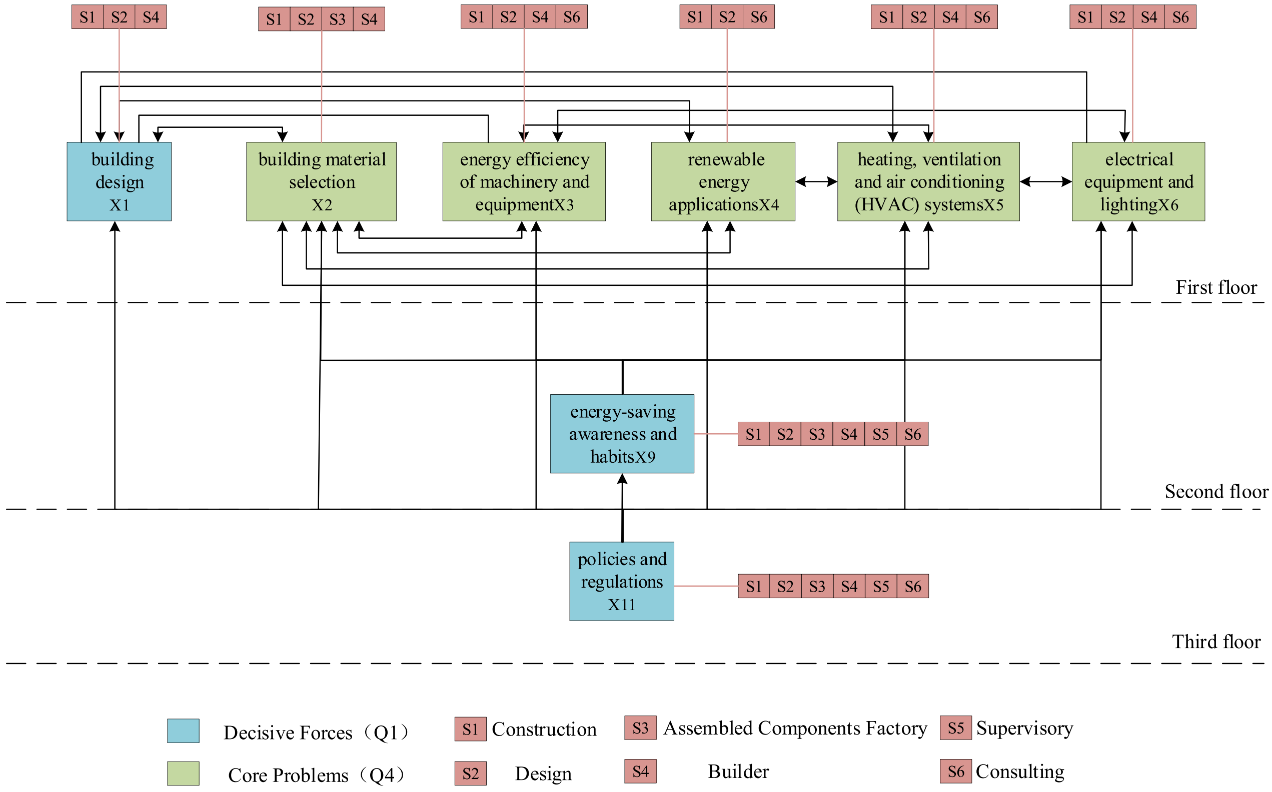

Figure 4. Hierarchy of important factors and key stakeholders.

supply chain, while the introduction of policies and regulations directly affects project design, material selection and equipment application. In addition, reasonable policy subsidies can motivate all parties to actively adopt low-carbon measures, such as increasing the application of renewable energy. Carbon emission reduction awareness affects people's behavior and choices to a certain extent, and individuals with low-carbon and energy-saving awareness are more inclined to choose low-carbon materials and equipment. Low-carbon measures also interact with each other, for example, building design affects the choice of building materials and equipment. Similarly, the choice to use low carbon materials and renewable energy equipment in order to improve the competitiveness of a company in a real project will also have an impact on building design.

4.3.5. DEMATEL-ISM analysis

In Figure 4, policies and regulations (X11) are at the bottom of the ISM hierarchical analysis, indicating that this factor has a very important role and status for the whole research system. Figure 3 shows that the (R+C) value of the policies and regulations (X11) indicator is much larger than the remaining two factors. Therefore, policies and regulations (X11) are the fundamental influence factor of CE from assembled buildings, and the control of CE should improve this factor from the root. We find that the factors located in Region IV are in the first tier of the relationship, and all of these factors have a common feature: their application will directly impact CE. Therefore, we can conclude that the five factors of building materials selection (X2); the energy efficiency of machinery and equipment (X3); renewable energy applications (X4); heating, ventilation, and air-conditioning (HVAC) systems (X5); and electrical equipment and lighting (X6) are the key direct influences. In Figure 4, the directed line segments indicate that a factor directly influences the factor pointed by the arrow. We can observe that the other two factors, building design (X1) and energy-saving awareness and habits (X9) in Region I, directly influence the five factors in Region IV. These factors change CE by influencing the key direct factors. At the same time, these two factors have high (R+C) values and significantly impact CE from assembled buildings, while also having a large impact on other factors. Therefore, we consider building design (X1) and energy-saving awareness and habits (X9) as key indirect influences. We should pay attention not only to the control factor itself but also to other factors involved in the factor in order to prevent a large indirect effect on the system when controlling CE. Stakeholders should focus on the factors related to them to avoid jeopardizing their interests due to changes in the factors.

4.4. Sensitivity analysis

Sensitivity analyses and correlation checks allow researchers to determine whether the possible biases of particular experts significantly impact the results of a study. In addition, sensitivity analyses make the results more generalizable or can be used to compare the perspectives of different stakeholders. In our study, we derived new factor rankings by this method by assigning higher weights (0.5) to different stakeholders and, keeping an even weight (0.1) to the rest of the stakeholders, introducing forced perturbations to test stability and generalizability, as shown in Tables 4 and 5.

Based on the results of the (R+C) value calculation and analysis, we observe that building materials selection (X2), as well as policies and regulations (X11), were ranked first in three out of six runs each. However, the overall cumulative value of the ranking of building materials selection (X2) was lower than that of policies and regulations (X11). Building design (X1) ranked second and third in five of the six runs. Therefore, these three factors still strongly influence the CE system of assembled buildings. Renewable energy applications (X4) and heating, ventilation, and air-conditioning (HVAC) systems (X5) were located in fourth place three and two times, respectively, out of six runs. However, the cumulative value of the former's ranking over the six runs was small, so a small re-ranking between these two factors is possible. Finally, energy-saving awareness and habits (X9) was ranked in the fifth, sixth, and seventh positions in four of the six runs, and it had the sixth-highest cumulative value of rankings. Overall, if we test the causal rankings based on the (R+C) values, the results deviate only slightly from Table 3.

Next, we observe the results of the (R-C) run calculations (Table 5). Due to the large gap between the rankings of the six runs of certain factors, the final ranking results are shown in the Table by combining the cumulative values of the six runs of each factor to assist in the ranking. Comparing Table 3, we observe that the ranking order of renewable energy applications (X4) and energy use monitoring and feedback (X10) are exchanged. However, their ranking cumulative values are 42 and 43, respectively, which is only one point difference; therefore, exchanging between these two factors does not significantly impact the analysis of the whole system. In addition, the ranking of water management (X13) has increased to 10th place from the original 12th place. However, in conjunction with the rankings in Table 4, building materials selection (X2) is still located in the fourth place in the causality

Table 4. Sensitivity analysis based on (R+C).

Factor	Construction	Design	Assembled components factory	Builder	Supervisory	Consulting	Rankings
X1- Building design	3	2	7	2	2	2	3
X2- Building material selection	2	3	6	1	1	1	1
X3- Energy efficiency of machinery and equipment	7	5	8	7	4	7	7
X4- Renewable energy applications	4	6	4	4	6	3	4
X5- Heating, ventilation, and air conditioning (HVAC) systems	6	4	2	5	3	4	5
X6- Electrical equipment and lighting	9	7	5	8	8	8	8
X7- Greening and landscaping	15	15	15	15	15	15	15
X8- Indoor environment optimization	13	13	12	14	14	12	13
X9- Energy-saving awareness and habits	5	8	3	6	7	6	6
X10- Energy use monitoring and feedback	8	10	11	9	11	10	10
X11- Policies and regulations	1	1	1	3	5	5	2
X12- Carbon trading and carbon market	10	9	10	10	9	9	9
X13- Water management	14	14	14	13	13	14	14
X14- Material recycling rate	11	11	13	11	12	13	11
X15- Construction waste disposal methods	12	12	9	12	10	11	12

Table 5. Sensitivity analysis based on (R-C).

Factors	Construction	Design	Assembled components factory	Builder	Supervisory	Consulting	Rankings
X1- Building design	2	4	3	4	2	2	2
X2- Building material selection	4	7	14	8	14	12	11
X3- Energy efficiency of machinery and equipment	6	13	15	12	15	9	14
X4- Renewable energy applications	5	10	4	5	12	6	4
X5- Heating, ventilation, and air conditioning (HVAC) systems	9	5	10	14	5	11	9
X6- Electrical equipment and lighting	7	3	7	13	6	8	6
X7- Greening and landscaping	11	9	6	6	7	13	8
X8- Indoor environment optimization	10	11	9	15	8	10	12
X9- Energy-saving awareness and habits	3	2	12	2	3	3	3
X10- Energy use monitoring and feedback	13	6	13	3	4	4	5
X11- Policies and regulations	1	1	1	1	1	1	1
X12- Carbon trading and carbon market	12	8	2	9	9	7	7
X13- Water management	14	15	5	7	11	5	10
X14- Material recycling rate	8	12	11	11	13	14	13
X15- Construction waste disposal methods	15	14	8	10	10	15	15

diagram due to its high (R+C) value – even though the increase in the ranking of water management (X13) has caused the ranking of building materials selection (X2) and indoor environment optimization (X8) to drop by one place. In contrast, factors with low (R+C) values, including construction waste disposal methods (X15), the energy efficiency of machinery and equipment (X3), material recycling rate (X14), water management (X13), and indoor environmental optimization (X8), remain early warning factors for CE from assembled buildings.

Based on the results of the above analysis, even if the stakeholder weights are changed, the (R+C) and (R-C) value rankings deviate only a little from Table 3. Therefore, managers can continue using our study's factor rankings and their causal relationships.

4.5. Stakeholder variability analysis

In the course of our study, we found that construction, design and assembled components factories considered policies and regulations (X11) to be the factors with the greatest degree of influence on the carbon emission system of assembled buildings, while supervisors, consultants and constructors considered the choice of building materials (X2) to be the most important factor.The field of assembled buildings is subject to various regulations, including building quality, safety, environmental protection, and sustainability. Builders and designers must ensure their projects comply with these regulations to avoid legal issues and delays. Prefabrication must ensure the builds meet quality standards to fulfill design and compliance needs. The selection of building materials directly affects the construction process and techniques, with builders selecting appropriate materials based on design specifications and construction requirements to ensure safety and durability. The supervision team oversees the construction process, while consulting units manage cost management and budget control, considering both material quality and availability. In summary, policies and regulations are crucial for compliance and sustainability, while construction, supervision, and consulting focus on material selection for quality and affordability. The scoring chart of fundamental influencing factors of different stakeholders is shown in Figure 5.

5. Discussions

Based on the results of the study we get that policies and regulations (X11) are the fundamental influences that affect carbon reduction in assembled buildings. The growing recognition of the importance of industrialised buildings in improving construction quality and enhancing environmental performance has led to increased scrutiny of supportive policies and regulations in many countries and regions (Li et al. 2019). However, despite accounting for more than half of the world's new construction floor space, assembly construction has not yet been fully embraced in mainland China (Jin et al. 2021). Lack of incentives for innovative policy tools is considered to be the biggest barrier to the introduction and implementation of energy efficiency and emission reduction policies in China (Huang, Mauerhofer, and Geng 2016). Strengthening international co-operation, learning from each other, and proposing more building energy efficiency as well as carbon trading mechanisms will further improve China's energy efficiency and emission reduction policies.

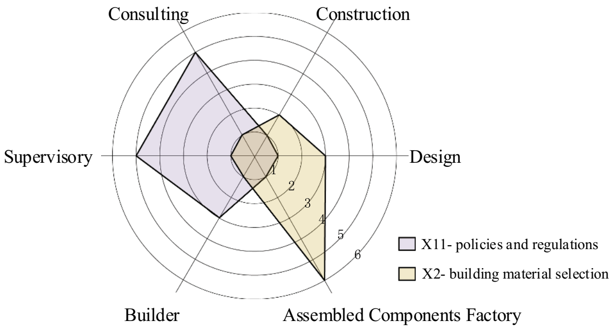

Figure 5. Scoring chart of fundamental influencing factors of different stakeholders.

As shown in Figure 4, the eight important factors are divided into three layers. Among these, energy efficiency awareness and habits (X9) influence factors such as the choice of materials and equipment and the application of renewable energy. Raising users' awareness of energy efficiency is crucial because their behaviour and habits directly affect carbon emissions during building operations (Bian et al. 2024). However, in this study, this factor does not only refer to the users' awareness of energy saving, but also the people involved in the whole life cycle of the assembled building, including designers, builders, users, operators and so on. Effective responses to global climate and environmental challenges can only be achieved when all building stakeholders consciously adopt energy saving and emission reduction measures. For example, at the design stage, by optimising the structural design of the building, reducing the amount of materials used and lowering the weight of the building, the energy consumption and carbon emissions during the transportation and installation of the building can be reduced. At the production stage, further carbon reduction strategies are achieved by increasing the use of green materials, introducing energy-efficient production processes, and improving the recycling rate of materials.

It is worth noting that some barriers are particularly important to certain stakeholders. For example, construction, design and assembled components factories consider policies and regulations (X11) to be the factor with the greatest degree of influence on the carbon system of assembled buildings, while supervisors, consultants and constructors consider the choice of building materials (X2) to be the most important factor. Stakeholders are more inclined to focus on the factors that hinder their development and less on other factors. This is also a good confirmation of the idea that the development of assembly building is still immature under the current market economic system, as the stakeholders involved in the process have not yet been able to form a good co-operation mechanism and are more inclined to retain their own interests (Huang et al. 2022). This poses a challenge to develop effective measures to incentivise all stakeholders to comply with the principles of energy conservation and emission reduction in the course of their actions. As suggested by Zhang et al. (2013), a participatory system should be established to facilitate communication among stakeholders.

Project decision-making involves multiple factors and is inherently complex. For example, Xu et al. (2020) showed that using sustainable materials can effectively reduce carbon emissions. However, this does not imply that all projects must prioritize reducing carbon emissions through material choices to achieve maximum carbon reduction. In some projects, the construction team may lack expertise in installing a particular sustainable material, or the material may need to be transported from a distant facility, thereby incurring significant costs and carbon emissions during transportation.

Similarly, the key factors identified in this study should serve as references for decision-makers and cannot be directly applied to every project. Therefore, during the decision-making process for carbon reduction in actual projects, decision-makers must engage in thorough communication and collaboration with participants in the prefabricated building supply chain. This collaboration should consider the specific conditions of the project to jointly determine the most appropriate carbon reduction measures based on existing research.

This study advances the understanding of carbon emissions in prefabricated buildings by providing a comprehensive framework that integrates both macro and micro-level factors influencing carbon reduction throughout the building's life cycle. Unlike previous research that often focuses on either broad policy implications or specific technical details, this study bridges the gap between these two approaches. At a macro level, the study emphasizes the importance of policies, supervision, and design strategies that promote energy efficiency and sustainable practices in the construction sector. At a micro level, it delves into critical factors such as individual behaviors, water and waste management practices, and the environmental properties of materials used, all of which directly impact carbon emissions.

The mixed-methods approach adopted in this study, combining bibliometric analysis with the Delphi method and DEMATEL-ISM modeling, provides a unique contribution by not only identifying key factors but also elucidating their interrelationships and hierarchical importance. This dual focus allows decision-makers to understand both the broader drivers of carbon emissions at the system level and the specific operational actions that can be taken at the project level.

The findings of this study serve as a valuable framework for decision-makers who need to implement carbon reduction strategies for specific projects. Using the proposed framework and calculation methods, decision-makers can develop effective carbon reduction measures under various scenarios. This study, therefore, enhances existing literature by offering a comprehensive approach that integrates insights across different levels of analysis, supporting the development of more effective carbon reduction strategies in prefabricated construction.

6. Conclusion

The study identifies key influencing factors affecting CE in prefabricated assembled buildings, focusing on energy efficiency and behavioral change over water and solid waste management and environmental properties. Among them, building material selection, energy efficiency of machinery and equipment, renewable energy applications, heating, ventilation and air conditioning (HVAC) systems, electrical equipment and lighting are the key influencing factors; policies and regulations are the fundamental influencing factors; building design, energy-saving awareness and habits are the indirect influencing factors. It also explores stakeholders' perspectives on CE influencing factors within the assembly building supply chain. Construction, designers, and assembled components factory identified policies and regulations as the factors with the greatest degree of influence on carbon emission systems in assembled buildings, while supervisors, consultants, and builders identified building material selection as the most important influence.The methodology and framework are adaptable to other engineering projects. The findings provide valuable insights for reducing carbon footprints and enhancing sustainability in the assembly building sector, offering valuable insights for reducing carbon footprints.

The study is limited to relying on the research literature and a limited number of experts and using a numerical scale instead of fuzzy language. Future work could benefit from a broader expert pool, especially in engineering practice. Additionally, the study could benefit from natural language processing techniques such as sentiment analysis for more nuanced quantification of expert perspectives. These considerations suggest opportunities for refining the research methodology and expanding its scope for a more comprehensive exploration of carbon emission influencing factors in assembled buildings in future studies.

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Jiang Xiaoyan: conceptualisation, methodology, access to funds; Xu Erman: writing – preparation of original drafts; He Shuxian: data collation; Martin Skidmore: Writing – review and editing.

Data availability statement

Data will be made available on request.

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Appendices

Appendix 1

DEMATEL-ISM model calculation steps and results

Step 1: The influencing factors of carbon emission of assembled buildings are named as X_1, X_2 , … … , X_n. ∂_{ij} denotes the direct influence of factor X_i on factor X_j, and the scoring criterion adopts the integer scale shown in Table A1 to get the direct relationship matrix $A=\left[\partial_{ij}\right]_{n\times n}$

Step 2: Triangular Fuzzy Number (TFN) is introduced to quantify the evaluation scale according to the fuzzy quantization formula to eliminate the subjective influence of expert scoring in order to obtain relatively accurate scoring results. The quantization formula for linguistic variables is as follows:

$$\bar{\partial}=\left(max\left\{\frac{r-2}{4},0\right\},\frac{r-1}{4},min\left\{\frac{r}{4},1\right\}\right) \tag{1}$$

The corresponding values of the linguistic variables calculated according to Equation (1) are shown in Table A2.

The CFCS (Converting the Fuzzy data into Crisp Scores) defuzzification method is utilized to convert the expert's triangular fuzzy evaluation language for carbon emission factors into a specific clear value. The CFCS method defuzzification process is operated as follows:

(1) Normalize the triangular fuzzy values. Let $l_{ij}^k, m_{ij}^k, u_{ij}^k$ be the normalized values of $a_{ij}^k, b_{ij}^k, c_{ij}^k$ respectively.

$$\begin{cases} l_{ij}^k=\dfrac{a_{ij}^k-\min\limits_{1\leq k\leq m} a_{ij}^k}{\Delta_{min}^{max}} \\ m_{ij}^k=\dfrac{b_{ij}^k-\min\limits_{1\leq k\leq m} a_{ij}^k}{\Delta_{min}^{max}} \\ u_{ij}^k=\dfrac{c_{ij}^k-\min\limits_{1\leq k\leq m} a_{ij}^k}{\Delta_{min}^{max}} \\ \Delta_{min}^{max}=\max\limits_{1\leq k\leq m} c_{ij}^k-\min\limits_{1\leq k\leq m} a_{ij}^k \end{cases} \tag{2}$$

(2) Calculate the normalized clear values of the upper and lower bounds of the fuzzy interval. Let r_{ij}^k and v_{ij}^k be the standardized clear values of the upper bound l_{ij}^k and lower bound u_{ij}^k respectively.

$$r_{ij}^k=\frac{m_{ij}^k}{1+m_{ij}^k-l_{ij}^k} \tag{3}$$

$$v_{ij}^k=\frac{u_{ij}^k}{1+u_{ij}^k-m_{ij}^k} \tag{4}$$

(3) Calculation of the total standardized precision value.

$$x_{ij}^k=\frac{r_{ij}^k\left(1-r_{ij}^k\right)+v_{ij}^k v_{ij}^k}{1-r_{ij}^k+v_{ij}^k} \tag{5}$$

(4) Calculate the clear value of the triangular fuzzy number.

$$d_{ij}^k=\min_{1\leq k\leq m} a_{ij}^k+x_{ij}^k\Delta_{min}^{max} \tag{6}$$

Step 3: Calculate the average direct relationship matrix M= $\left[m_{ij}\right]_{n\times n}$.

$$M=\frac{1}{q}\sum_{1}^{q}\left[d_{ij}\right]_{n\times n} \tag{7}$$

The results of the calculations are shown in Table A3.

Step 4: Normalized matrix N=$\left[n_{ij}\right]_{n\times n}$.

$$N=\frac{1}{\max\limits_{1\ll i\ll n}\sum_{j=1}^{n}\partial_{ij}}M \tag{8}$$

The results of the calculations are shown in Table A4.

Step 5: Total direct relationship matrix T=$\left[t_{ij}\right]_{n\times n}$.

$$T=N(I-N)^{-1} \tag{9}$$

The results of the calculations are shown in Table A5.

The factor influence can be calculated once the total direct relationship matrix T is obtained, R is the sum of the rows of T, and C is the sum of the columns of T. The formula is as follows:

Table A1. Factor rating scale.

Linguistic term	Influence score
No influence	1
Very low influence	2
Low influence	3
High influence	4
Very high influence	5

Table A2. Corresponding values of linguistic variables.

Influence score	triangular fuzzy number
1	(0,0,0.25)
2	(0,0.25,0.5)
3	(0.25,0.5,0.75)
4	(0.5,0.75,1)
5	(0.75,1,1)

Table A3. Average direct relationship matrix M.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
X_1	0.000	0.821	0.578	0.685	0.792	0.743	0.636	0.597	0.413	0.442	0.500	0.481	0.539	0.588	0.471
X_2	0.704	0.000	0.636	0.588	0.607	0.588	0.462	0.597	0.539	0.471	0.529	0.529	0.452	0.714	0.665
X_3	0.549	0.529	0.000	0.471	0.704	0.733	0.364	0.432	0.559	0.549	0.442	0.568	0.539	0.510	0.500
X_4	0.568	0.607	0.539	0.000	0.626	0.617	0.393	0.442	0.617	0.549	0.587	0.617	0.588	0.500	0.520
X_5	0.665	0.646	0.733	0.607	0.000	0.656	0.364	0.559	0.617	0.607	0.500	0.578	0.403	0.364	0.413
X_6	0.597	0.558	0.675	0.549	0.704	0.000	0.423	0.636	0.675	0.597	0.481	0.510	0.335	0.345	0.384
X_7	0.510	0.442	0.374	0.413	0.384	0.423	0.000	0.471	0.423	0.364	0.481	0.442	0.549	0.393	0.461
X_8	0.549	0.588	0.500	0.491	0.500	0.549	0.481	0.000	0.558	0.374	0.423	0.374	0.442	0.432	0.413
X_9	0.510	0.617	0.587	0.685	0.646	0.646	0.520	0.568	0.000	0.481	0.462	0.461	0.578	0.549	0.597
X_{10}	0.481	0.471	0.549	0.685	0.588	0.578	0.335	0.413	0.461	0.000	0.520	0.529	0.607	0.481	0.423
X_{11}	0.753	0.733	0.675	0.675	0.646	0.578	0.626	0.529	0.607	0.685	0.000	0.724	0.685	0.695	0.743
X_{12}	0.452	0.587	0.539	0.539	0.558	0.490	0.432	0.393	0.510	0.549	0.559	0.000	0.481	0.520	0.491
X_{13}	0.481	0.393	0.491	0.520	0.432	0.316	0.500	0.471	0.549	0.539	0.539	0.471	0.000	0.432	0.491
X_{14}	0.578	0.636	0.510	0.500	0.374	0.345	0.384	0.442	0.587	0.461	0.461	0.452	0.384	0.000	0.665
X_{15}	0.510	0.685	0.471	0.491	0.364	0.335	0.423	0.413	0.520	0.481	0.510	0.558	0.364	0.597	0.083

Table A4. Normalized direct relationship matrix N.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
X_1	0.000	0.088	0.062	0.073	0.085	0.079	0.068	0.064	0.044	0.047	0.053	0.051	0.058	0.063	0.050
X_2	0.075	0.000	0.068	0.063	0.065	0.063	0.049	0.064	0.058	0.050	0.057	0.057	0.048	0.076	0.071
X_3	0.059	0.057	0.000	0.050	0.075	0.078	0.039	0.046	0.060	0.059	0.047	0.061	0.058	0.055	0.054
X_4	0.061	0.065	0.058	0.000	0.067	0.066	0.042	0.047	0.066	0.059	0.063	0.066	0.063	0.053	0.056
X_5	0.071	0.069	0.078	0.065	0.000	0.070	0.039	0.060	0.066	0.065	0.053	0.062	0.043	0.039	0.044
X_6	0.064	0.060	0.072	0.059	0.075	0.000	0.045	0.068	0.072	0.064	0.051	0.055	0.036	0.037	0.041
X_7	0.055	0.047	0.040	0.044	0.041	0.045	0.000	0.050	0.045	0.039	0.051	0.047	0.059	0.042	0.049
X_8	0.059	0.063	0.054	0.052	0.053	0.059	0.051	0.000	0.060	0.040	0.045	0.040	0.047	0.046	0.044
X_9	0.055	0.066	0.063	0.073	0.069	0.069	0.056	0.061	0.000	0.051	0.049	0.049	0.062	0.059	0.064
X_{10}	0.051	0.050	0.059	0.073	0.063	0.062	0.036	0.044	0.049	0.000	0.056	0.057	0.065	0.051	0.045
X_{11}	0.081	0.078	0.072	0.072	0.069	0.062	0.067	0.057	0.065	0.073	0.000	0.077	0.073	0.074	0.079
X_{12}	0.048	0.063	0.058	0.058	0.060	0.052	0.046	0.042	0.055	0.059	0.060	0.000	0.051	0.056	0.052
X_{13}	0.051	0.042	0.052	0.056	0.046	0.034	0.053	0.050	0.059	0.058	0.058	0.050	0.000	0.046	0.052
X_{14}	0.062	0.068	0.055	0.053	0.040	0.037	0.041	0.047	0.063	0.049	0.049	0.048	0.041	0.000	0.071
X_{15}	0.055	0.073	0.050	0.052	0.039	0.036	0.045	0.044	0.056	0.051	0.055	0.060	0.039	0.064	0.009

Table A5. Total direct relationship matrix T.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
X_1	0.247	0.340	0.304	0.314	0.327	0.313	0.263	0.279	0.281	0.269	0.270	0.277	0.271	0.282	0.276
X_2	0.311	0.254	0.304	0.300	0.304	0.293	0.242	0.274	0.287	0.267	0.267	0.276	0.258	0.290	0.290
X_3	0.279	0.288	0.223	0.271	0.296	0.290	0.218	0.243	0.272	0.259	0.243	0.264	0.250	0.253	0.257
X_4	0.290	0.306	0.287	0.233	0.298	0.288	0.229	0.252	0.287	0.268	0.266	0.278	0.264	0.262	0.269
X_5	0.299	0.308	0.305	0.293	0.235	0.292	0.225	0.263	0.286	0.272	0.257	0.273	0.246	0.248	0.257
X_6	0.285	0.292	0.292	0.280	0.298	0.219	0.225	0.264	0.285	0.264	0.248	0.260	0.233	0.239	0.247
X_7	0.237	0.239	0.223	0.227	0.226	0.222	0.150	0.212	0.222	0.206	0.213	0.216	0.218	0.208	0.219
X_8	0.257	0.270	0.252	0.251	0.254	0.251	0.212	0.179	0.251	0.221	0.222	0.225	0.222	0.226	0.229
X_9	0.287	0.309	0.294	0.303	0.302	0.293	0.242	0.266	0.228	0.263	0.256	0.265	0.265	0.268	0.278
X_{10}	0.263	0.273	0.269	0.283	0.275	0.266	0.208	0.232	0.255	0.195	0.243	0.252	0.250	0.243	0.242
X_{11}	0.351	0.363	0.342	0.343	0.342	0.325	0.286	0.298	0.327	0.319	0.245	0.328	0.311	0.320	0.330
X_{12}	0.260	0.283	0.268	0.268	0.272	0.257	0.217	0.230	0.258	0.250	0.246	0.198	0.237	0.246	0.248
X_{13}	0.248	0.250	0.248	0.252	0.245	0.226	0.212	0.224	0.248	0.236	0.232	0.233	0.176	0.225	0.235
X_{14}	0.263	0.279	0.255	0.255	0.245	0.234	0.205	0.226	0.256	0.232	0.229	0.235	0.219	0.186	0.257
X_{15}	0.257	0.284	0.252	0.255	0.244	0.233	0.209	0.224	0.250	0.235	0.234	0.246	0.218	0.247	0.199

$$\boldsymbol{R} = \left[\sum_{i=1}^{n} \boldsymbol{t_{ij}}\right]_{n\times 1}, \boldsymbol{C} = \left[\sum_{J=1}^{n} \boldsymbol{t_{ij}}\right]_{1\times n} \tag{10}$$

Step 6: Validate the results of the DEMATEL analysis with the help of a second group of experts and revisit the available literature if needed. If there are significant deviations in the results, they will be communicated to the experts and the responses will be collected again and organized for re-analysis.

Step 7: Based on the DEMATEL analysis, the factors that have an important influence on the carbon emissions of assembled buildings are initially extracted, and the thresholds are calculated based on the data in matrix T (Table A5) to form a new matrix T1 (Table A6).

Decision makers need to set thresholds for factor levels in order to obtain plausible causality maps and to provide data for the reachability matrices needed for subsequent ISM analyses. In established studies, there are five broad approaches to threshold setting as follows:

(1) through expert discussion
(2) Averaging over the total direct relationship matrix T
(3) Adding a standard deviation to the mean value of the total direct relationship matrix T
(4) Adding two standard deviations to the mean of the total direct relationship matrix T
(5) Apply the maximum mean de-entropy algorithm

In this paper, we choose method 2 to take the average value of the total direct relationship matrix T taken as the threshold λ, which is calculated as follows:

$$\lambda = \frac{1}{\boldsymbol{n}^2} \sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \sum_{\boldsymbol{j}=1}^{\boldsymbol{n}} \boldsymbol{t_{ij}} \tag{11}$$

Calculated result: $\lambda = 0.289$

Step 8: Total Impact Matrix H = $\boldsymbol{h_{ij_{n\times n}}}$.

$$\boldsymbol{H} = \boldsymbol{T}_1 + \boldsymbol{I} \tag{12}$$

The results of the calculations are shown in Table A7.

Step 9: The reachability matrix K = $\boldsymbol{k_{ij_{n\times n}}}$is obtained by the new threshold setting and is calculated as follows:

$$\boldsymbol{k_{ij}} = \begin{cases} \mathbf{1}, \boldsymbol{h_{ij \gg \lambda}} \\ \mathbf{0}, \boldsymbol{h_{ij < \lambda}} \end{cases}. \tag{13}$$

Table A6. Direct relationship matrix of significant influencing factors T1.

	X_1	X_2	X_3	X_4	X_5	X_6	X_9	X_{11}
X_1	0.247	0.340	0.304	0.314	0.327	0.313	0.281	0.270
X_2	0.311	0.254	0.304	0.300	0.304	0.293	0.287	0.267
X_3	0.279	0.288	0.223	0.271	0.296	0.290	0.272	0.243
X_4	0.290	0.306	0.287	0.233	0.298	0.288	0.287	0.266
X_5	0.299	0.308	0.305	0.293	0.235	0.292	0.286	0.257
X_6	0.285	0.292	0.292	0.280	0.298	0.219	0.285	0.248
X_9	0.287	0.309	0.294	0.303	0.302	0.293	0.228	0.256
X_{11}	0.351	0.363	0.342	0.343	0.342	0.325	0.327	0.245

Table A7. Total impact matrix of significant influencing factors H.

	X_1	X_2	X_3	X_4	X_5	X_6	X_9	X_{11}
X_1	1.247	0.340	0.304	0.314	0.327	0.313	0.281	0.270
X_2	0.311	1.254	0.304	0.300	0.304	0.293	0.287	0.267
X_3	0.279	0.288	1.223	0.271	0.296	0.290	0.272	0.243
X_4	0.290	0.306	0.287	1.233	0.298	0.288	0.287	0.266
X_5	0.299	0.308	0.305	0.293	1.235	0.292	0.286	0.257
X_6	0.285	0.292	0.292	0.280	0.298	1.219	0.285	0.248
X_9	0.287	0.309	0.294	0.303	0.302	0.293	1.228	0.256
X_{11}	0.351	0.363	0.342	0.343	0.342	0.325	0.327	1.245

Table A8. Reachability matrix K.

	X_1	X_2	X_3	X_4	X_5	X_6	X_9	X_{11}
X_1	1	1	1	1	1	1	0	0
X_2	1	1	1	1	1	1	0	0
X_3	0	0	1	0	1	1	0	0
X_4	1	1	0	1	1	0	0	0
X_5	1	1	1	1	1	1	0	0
X_6	0	1	1	0	1	1	0	0
X_9	0	1	1	1	1	1	1	0
X_{11}	1	1	1	1	1	1	0	0

Table A9. Reachable sets, antecedent sets and intersection sets.

n	Reachable sets	antecedent sets	intersection sets
1	[1,2,3,4,5,6]	[1,2,3,4,5,6,9,11]	[1,2,3,4,5,6]
2	[1,2,3,4,5,6]	[1,2,3,4,5,6,9,11]	[1,2,3,4,5,6]
3	[1,2,3,4,5,6]	[1,2,3,4,5,6,9,11]	[1,2,3,4,5,6]
4	[1,2,3,4,5,6]	[1,2,3,4,5,6,9,11]	[1,2,3,4,5,6]
5	[1,2,3,4,5,6]	[1,2,3,4,5,6,9,11]	[1,2,3,4,5,6]
6	[1,2,3,4,5,6]	[1,2,3,4,5,6,9,11]	[1,2,3,4,5,6]
9	[1,2,3,4,5,6,9]	[9,11]	[9]
11	[1,2,3,4,5,6,9,11]	[11]	[11]

The results of the calculations are shown in Table A8.

The MATLAB software was used to calculate K_1, K_2, …… and Kn. It was found that the self-multiplication result is unchanged for n ≥ 2.

According to the calculation results in Table A9, the eight important influencing factors are categorized into three tiers. The first tier consists of six factors: building design (X1), building materials selection (X2), energy efficiency of machinery and equipment (X3), renewable energy applications(X4), heating, ventilation and air conditioning (HVAC) system (X5), and electrical equipment and lighting (X6). The second tier of factors is energy-saving awareness and habits (X9). The third tier factors are policies and regulations (X11).

Appendix 2

Initial Table of Carbon Emission Influencing Factors for Assembled Buildings

Serial No.	Factors	Serial No.	Factors
1	Building Structure Selection	13	Application of new technologies and techniques
2	Building Material Selection	14	Living area water and electricity management
3	Public Services and Facilities Planning	15	Construction organization design and management
4	Building site selection and site quality	16	Energy efficiency of construction machinery
5	Building Life Cycle	17	Construction progress control
6	Low Carbon Institutions and Policy Incentives	18	Construction quality control
7	Low Carbon Material Utilization	19	Residents' Carbon Emission Awareness
8	Prefabricated factory production technology level	20	Energy efficiency of operation equipment
9	Energy efficiency of production machinery and equipment	21	Application of renewable energy
10	Material recycling utilization rate	22	Energy efficiency of dismantling machinery and equipment
11	Distance between raw material extraction and plant location	23	Recycling rate of building materials and components
12	Transportation solutions	24	Demolition Standardization

Appendix 3

Questionnaire on the relationship between factors affecting carbon emissions from assembled buildings

Dear Sir/Madam:

Greetings! I am a graduate student of Hefei University of Technology, thank you very much for being able to participate in this questionnaire survey in your busy schedule. The purpose of this survey is to understand the relationship between the various influencing factors of carbon emission of assembly buildings, in order to help us study carbon emission reduction of assembly buildings in a more in-depth manner. The results of this survey are only used for academic research, you can feel free to fill in the real results, thank you for your participation and cooperation!

You need to score the influencing factors in the table below according to the following evaluation scale and give a rating in the corresponding table.

Linguistic term	Influence score
No influence	1
Very low influence	2
Low influence	3
High influence	4
Very high influence	5

Note 1: If you encounter two factors that cannot be scored accurately, please elaborate in a short sentence on some kind of relationship that exists between the two factors for subsequent research.

Note 2: Since this study involves subjective rating, in order to facilitate the discussion of whether factor importance and relationships are influenced by the subjectivity of the expert, it is necessary for the rating expert to provide his/her field of study, position, and experience, please fill in your position after your field below and check the box for work experience.

Construction_____ Design_____ Builder_____.

PC component_____ factory_____ Supervision_____ Consulting_____.

Experience (for years): 5–10☐ 10–15☐ 15–20☐
20-25☐ 25-30☐ 30+☐

j i	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15
X1- building design	\														
X2-building material selection		\													
X3-energy efficiency of machinery and equipment			\												
X4- renewable energy applications				\											
X5- heating, ventilation and air conditioning (HVAC) systems					\										
X6- electrical equipment and lighting						\									
X7- greening and landscaping							\								
X8-indoor environment optimization								\							
X9- energy-saving awareness and habits									\						
X10- energy use monitoring and feedback										\					
X11- policies and regulations											\				
X12- carbon trading and carbon market												\			
X13- water management													\		
X14- material recycling rate														\	
X15- construction waste disposal methods															\