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Identifying Critical Factors Affecting the Resilience of Additive Manufacturing Architecture Supply Chain

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Abstract: Building a resilient and stable supply chain has become an important strategy for many countries. Studies have shown that the application of additive manufacturing (AM) technology in construction can help offset the negative impact of "black swan events" on supply chains. This study examines the construction industry based on AM technology and analyzes the impact of changes in the industry chain on the supply chains. The specific factors that affect the resilience of AM construction supply chains were identified through literature research and expert interviews, including 7 dimensions and 21 secondary indicators. An intuitionistic fuzzy analytic hierarchy process (IFAHP) evaluation model was established. Finally, an example of an AM construction manufacturer, YC Enterprise, was introduced to quantify the various factors and determine the weights. The results show that the essence of building a supply chain with AM is creating a closed-loop supply chain. The impact of AM construction manufacturers on supply chain resilience (SCR) is the most critical, followed by that of regulatory authorities and general contractors. The AM construction SCR assessment index system and evaluation method constructed in this paper have important significance in filling the gap in the quantitative evaluation of the impact of AM on supply chains.

Keywords: additive manufacturing; supply chain resilience; intuitionistic fuzzy analytic hierarchy process

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1. Introduction

The COVID-19 pandemic in recent years has had a huge impact on supply chains in many industries around the world. In October 2021, a serious supply chain disruption crisis erupted in the West Coast ports of the United States, with containers piling up in the ports and the prices of items in supermarkets reaching unprecedented levels. The reason for this was the disruption of the supply chain and the collapse of the entire logistics system due to the labor shortage caused by the pandemic. Similar 'black swan' events such as the COVID-19 pandemic have raised concerns about supply chain stability across all industries. It is of great significance to prevent "supply chain disruption" and enhance supply chain resilience (SCR), as this can effectively mitigate the impact of risks on enterprises and improve their risk resistance capabilities [1].

Sloppy management and low industry concentration are the downfalls of the construction industry. The COVID-19 pandemic has resulted in poorly coordinated supply chains, long cycle times and plummeting revenues and profits for construction companies. In recent years, as additive manufacturing (AM) technology has matured, many academics and companies have seen its promise and potential in the construction industry [2]. Many studies have suggested that AM, as a flexible manufacturing technology with low energy consumption and emissions, can easily be applied to new energy sources and emerging technologies such as big data and artificial intelligence to achieve cross-border integration and multi-scenario overlap, supporting the improvement of SCR and construction quality.

AM, also known as 3D printing, is a manufacturing process in which materials are added layer by layer to create a physical object based on a 3D computer model. This is different from traditional "subtractive manufacturing" in which raw materials are removed, cut, or shaped to create the final product [3]. According to the standards jointly published by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO), AM can be classified into seven different types, including stereolithography, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, and sheet lamination [4]. In the field of architecture, material extrusion and binder jetting are widely used AM technologies. The ink material used in AM architecture consists of three parts: binder materials, reinforcement materials, and additives, which differ significantly from traditional concrete, making the manufacturing process more complex and diverse. Compared with traditional manufacturing technologies, AM benefits from its unique manufacturing method, which significantly increases the geometric freedom of the model, reduces material waste and dependency on human labor, and reduces manufacturing costs and times [5]. Although AM technology has been widely used in other industries, its development in the construction industry has been relatively slow due to certain limitations, such as insufficient material structural performance and immature printer technology. However, with the continuous progress of technology, the application of AM technology in the construction industry will gradually expand, bringing new vitality to the industry.

The AM architecture supply chain differs from the traditional architecture supply chain. It involves more companies and is more complex, which increases the uncertainty factors in the operation process. Therefore, supply chain management has become even more important, and there is currently a lack of fundamental discussion and research on the AM architecture supply chain. Although the literature has shown that AM can improve supply chain resilience, there is a lack of quantitative research on the supply chain toughness of AM buildings, with most studies focusing on materials and qualitative studies of AM buildings [6]. Therefore, the aims of this study are to explore the application of AM in the construction industry and its impact on the supply chain, to identify the key influences on SCR, and to improve SCR. As a technology that can revolutionize the supply chain in the construction industry, a study of how AM affects the supply chain is important to promote the adoption of AM, related research, and understanding by policymakers. The evaluation index system and the evaluation method constructed in this paper are important for quantitatively assessing the impact of AM on SCR, bridging the gap in this field.

AM construction technology will lead to a restructuring of the entire construction industry chain, which will have a profound impact on the system and structure of the supply chain. A complete supply chain analysis should be based on the changes in the industry chain caused by AM construction technology. Therefore, in Section 2, the construction industry chain based on AM technology is presented. Section 3 empirically investigates the supply chain structure of an AM enterprise, discusses the impact of the industrial chain on the supply chain, and establishes an SCR evaluation index system. Section 4 uses the intuitionistic fuzzy analytic hierarchy process (IFAHP) to analyze the impact of AM on the supply chain from a quantitative perspective.

2. Literature Review

2.1. SCR

SCR has been interpreted differently by different scholars. However, the common viewpoint is that it indicates the ability of a supply chain to recover and continue to operate after being exposed to risks and disturbances, i.e., the ability to maintain supply and return to normal when the supply chain is subject to fluctuations or even interruptions, such as due to COVID-19 pandemic, supply disruptions, etc. [7]. If a supply chain is less resilient, then in the event of a risk or unexpected event, there is a high risk that the entire supply chain will collapse, causing many enterprises to cease to exist.

In recent years natural disasters, political conflicts, economic crises, and the COVID-19 pandemic have brought huge potential risks and shocks to supply chains. For the construction industry in particular, which is characterized by uncertainty, complex structures, and large internal and external resources, the impact has been even more significant. When an epidemic hits, the risk can quickly ripple from the nodes to the entire supply chain. As an important tool to resist sudden risks, improving SCR is of great significance to enterprises in coping with risks and improving industry profits [8].

Research methods on the factors influencing SCR can be divided into qualitative and quantitative research methods. Qualitative research methods are mainly based on case studies, while quantitative research methods are mainly based on decision analysis methods. For example, QIAN et al. [9], ZHU et al. [10], and FAN et al. [11] established evaluation index system from different perspectives and used hierarchical analysis, an explanatory structural model, and the TOPSIS method to analyze the SCR of assembly construction and its key influencing factors, pointing out the current realistic problems such as high production costs, low standardization, and supply delays in assembly construction enterprises. Delic [12] used the PLS-SEM model to analyze the impact of AM. The results show that AM technology has a positive impact on SCR, providing a basis for AM technology to improve SCR. Rinaldi et al. [13] used a multi-criteria decision-making approach based on the environmental and economic aspects of AM to demonstrate that AM contributes to the formation of a green supply chain.

In terms of supply chain model construction, Zhang et al. [14] established a supply chain multi-entity collaborative relationship model based on a systematic analysis of the participating subjects, value streams, and process stages of the construction supply chain. However, such models are applicable to assembly buildings and do not meet the characteristics of AM buildings. SHI [15] et al. applied a hierarchical clustering–TOPSIS integrated evaluation model to evaluate the problem of identifying key nodes in the green supply chains of assembled buildings.

There is a lack of research on the resilience of AM building supply chains. Rahman et al. proposed a comprehensive evaluation method based on the Dempster–Shafer theory to assess the resilience of an AM building supply chain network [16]. The study showed that the AM supply chain has good resilience and that the maximum impact of AM on the supply chain is in logistics and inventory management. Although there may be network threats due to technology and information sharing, AM balances the risks by reducing some suppliers and node companies, forming good supply chain network resilience. Khan and Sepúlveda Estay studied SCR and the potential risks it can face [17]. They analyzed existing supply chain risk and resilience frameworks and established the research scope on supply chain resilience.

Overall, there is currently no established evaluation system for the resilience of AM building supply chains, and there is a lack of summary and analysis of the inherent connections between existing AM technologies and supply chains and industry chains. This makes it impossible to measure the ability of AM building supply chains to respond to external risks or determine the key factors that affect SCR in the event of unexpected events. This inevitably affects the scientific validity of the evaluation results.

2.2. The Impact of AM on a Supply Chain

In recent years, AM technology has played an important role in improving production methods and enhancing supply chain capabilities. This technology has the potential to allow manufacturers to change their production processes and reduce production steps. As a result, not only does production and its processes need to be redesigned, but it also affects the supply network and logistics. The current research primarily focuses on AM's impact on and transformation of existing industrial supply chains. Although existing research has recognized the potential impact of AM on supply chains, it is difficult to quantify. Therefore, the evaluation of the impact of AM on the supply chain is mainly qualitative, with only a few quantitative evaluations.

Corsini et al. analyzed the impact of 3D printing on the supply chain from a humanitarian perspective. The research results indicate that 3D printing will fundamentally change the way products are designed and manufactured, and it will affect the humanitarian supply chain in four aspects: network, governance, process, and product. However, it is not necessarily the case that 3D printing will simplify and shorten the supply chain [18]. Attaran et al. explored the impact of AM on the global supply chain and logistics, and the research showed that AM can improve the efficiency of the entire supply chain [19]. Belhadi et al. argue that the advantages of AM lie in the dematerialization of the supply chain, which reduces the time required for management, transformation, and assembly. Dematerialization of the supply chain refers to the simplification or even elimination of many physical world processes such as storage and construction in the traditional building supply chain [20].

From a qualitative research perspective, AM has empowered various industries and has had a significant impact on the enterprises and processes involved in supply chains. The main impacts are as follows: (1) AM can produce a significant reduction in the number of suppliers [21]. AM does not require assembly operations, so it can minimize the demand for semi-finished products and inventory. The combination of these factors has led to improved logistics efficiency, reduced supplier numbers, and profound changes in the relationships between partners in the supply chain. (2) The impact on the global supply chain may be disruptive [22]. This technology has the potential to replace a large number of traditional factories and low-skilled workers, thereby significantly reducing the cost of a supply chain. Manufacturing can be carried out anywhere at similar costs, leading to more home workshops and community factories. Therefore, global production will no longer be significantly economically beneficial, and this technology may restructure the global supply chain. (3) AM can reshape the logistics industry [23]. AM can significantly shorten product delivery times, reduce costs, and completely reform the logistics industry. The logistics industry may generate new businesses or models that specialize in the storage and transportation of ink materials. (4) AM can improve production and distribution flexibility [24]. AM has a significant impact on production and distribution. Customers can participate in design and production, and manufacturers can customize personalized products for each customer in stages. AM may reduce costs and increase profits.

In summary, AM technology can affect a supply chain in many ways, including accelerating product development, reducing economic batch sizes, increasing production flexibility, and reducing material waste, allowing companies to profit from raw material procurement, logistics, and product distribution. This paper will build upon existing research on the impact of AM on supply chains and provide a specific analysis of how AM affects supply chains in the construction industry.

2.3. Application of AM Technology in Construction

AM technology can be used not only in print facilities and houses but also for different uses and scenarios. Sorting out the application of AM technology in the construction industry requires understanding the AM construction industry chain and supply chain structure and building an SCR evaluation index system [25].

During the design phase, AM technology contributes to the digitization of construction. It supports the creation of a data-sharing platform that includes printing software, BIM (building information modeling), and clients and designers [26]. AM offers significant advantages in printing customized components with low production costs and high efficiency for personalized designs, while BIM provides data support for AM, providing accurate spatial positioning information for the printing of buildings and enabling high-precision printing. Secondly, AM contributes to topology optimization, a promising and future-proof technology that uses less material to achieve more functionality by changing shapes and structures.

In the building printing phase, AM technology can either print on-site or on print walls and then assemble them. Figure 1 shows the process of printing and assembling an AM

building. AM construction can be divided into two types. The first type is on-site printing, which involves directly printing the building on the construction site or in a factory. The second type involves printing the components in a factory and then transporting them to the site for assembly. Figure 1 shows the second type of AM construction. On-site printing does not require steps 7 to 10. The components are first printed in a factory, and after the foundations are completed on the construction site, they are transported to the construction site for assembly, followed by the partial pouring of concrete and finally finishing the façade, a process that is similar to the construction of an assembled building. Pipes, windows, reinforcement, etc., are pre-positioned at the design stage, and reinforcement is added to the hollow sections of the elements prior to the secondary pouring to increase the overall strength and tensile properties of the wall, or different insulation or soundproofing materials can be added to reduce weight and achieve different functions [27].

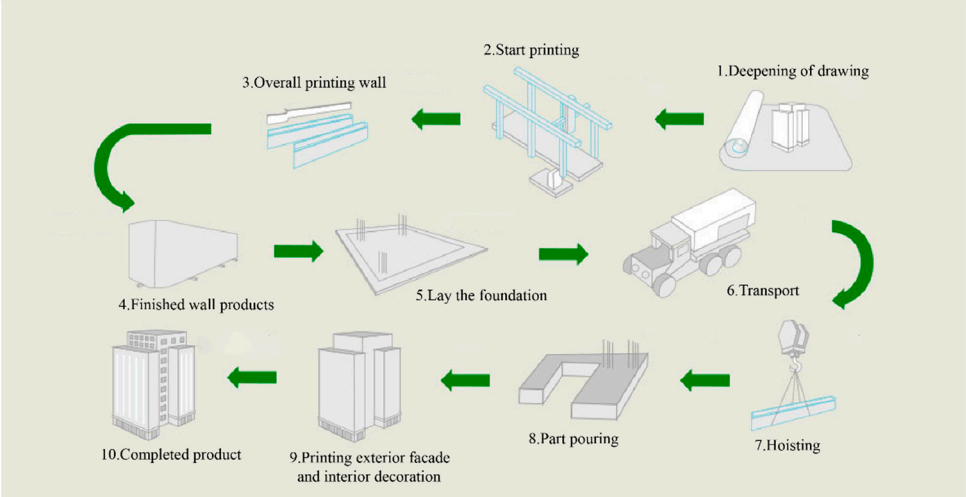


Figure 1. The process of building printing and assembly in AM.

AM allows for the accurate printing of the formwork for components. In assembly construction, the quality of the formwork determines the quality of the components, and most formwork is not recyclable [28]. The stencil can be fully recycled after use, is malleable, quicker to produce, and has higher precision.

The potential of AM in the construction industry lies not only in the design and construction of buildings but also in logistics and waste recycling. Due to their size and vulnerability to damage, construction components require strict protective measures during transport, storage, and lifting. There are, therefore, high demands on logistics and storage. AM allows flexible production and reduces the pressure on inventories. Manufacturers can take advantage of AM's ability to produce on-demand components that customers need in a timely manner, reducing inventory costs. The raw materials of printing ink can be construction waste, manufacturing waste and leftovers, mine tailings, and coal gangue. This reduces costs and mitigates damage to the environment and promotes the green upgrading of the traditional construction industry. The application of AM in the construction industry is comprehensive and profound, affecting the entire industry chain, and will certainly reshape the whole industry and form a new industry business model.

Currently, there are still some defects in using AM for construction: (1) The insufficient performance of printing materials: Existing materials have poor durability and cannot meet the long-term outdoor requirements of buildings. There is a lack of a mathematical model or relationship between the slurry composition and rheological properties based on different working conditions, such as temperature, humidity, the printing scale, and the printing layer interval time. There is also a lack of additives that can finely control the ink performance, such as enhancers and thickeners [29]. (2) The printing equipment does not meet environmental requirements: Due to limitations in existing printing equipment

and printing programs, complex components can only be produced using assembly techniques. The height of AM building floors is generally limited to one or two stories, and 3D printers used for construction must ensure precision and high integration. Existing AM concrete equipment still cannot fully meet the special requirements of different application environments. (3) Poor structural performance: As the layer height increases, reinforcing structures are necessary to ensure seismic resistance in buildings. How to combine printing equipment and construction processes to achieve high-toughness building structures is still a major problem that needs to be solved [30].

3. Construction Industry Based on AM Technology

AM supports improving supply chain agility. AM has an important role to play in lean manufacturing and agile supply chains. Therefore, does AM in the construction industry support the improvement of supply chain agility? Before carrying out the relevant research, it is necessary to understand how AM construction technology has changed chains. Figure 2 shows a spillover chain based on AM construction technology [31]. The industry chain is established from the perspective of YC enterprises. YC is a AM construction manufacturer based in China, with 20 years of experience in the field and abundant AM construction products. Its main roles in the supply chain are in construction printing, material supply, and equipment supply. The industry chain in which YC operates is developed and mature, and it has significant research value.

In a previous article, we summarized the applications of AM technology in the construction industry. However, the real potential of AM technology is not limited to housing but can also be extended outwards to all kinds of engineering buildings, infrastructure, and other fields, forming an industry with AM construction technology as its core. AM construction technology will lead to a restructuring of the entire construction industry chain, which will inevitably have a profound impact on the industry's supply chain system and structure.

As shown in Figure 2, the future application scenario of AM is divided into three segments: a green city, transportation, and countryside. Industrial bases are established on a city-by-city basis, with a circular supply chain formed internally. The upstream recycling and processing of city-generated waste provides raw materials for builders, and midstream modern equipment manufacturing bases are responsible for promoting industrial optimization and building empowerment, and downstream industrialized application demonstration bases are established to enable technology sharing and guidance.

YC enterprises provide full support to companies in the supply chain in terms of raw materials and technology by building bases and industrial chains around the city. Innovative technologies such as 5G, artificial intelligence, big data, cloud computing, blockchain, and industrial internet are combined with AM for application, ultimately realizing the informatization, digitization, and intelligence of the construction industry. From Figure 2, it can be seen that AM-related technologies are expected to be applied to a number of industries and scenarios. Waste processing technology as a key technology drives a supply chain and industry chain to form a closed loop. The waste generated by construction sites and factories are classified and crushed and then become some of the raw materials for printing ink. Finally, the ink becomes a component and returns to the building. A green city, transportation, and countryside are the application scenarios, and these three bases are the means of the realization, and the intelligence, digitization, and informatization of the construction industry is the ultimate goal [32].

The application of AM encompasses multiple aspects and levels of the construction industry, with infrastructure as the root, radiating outwards to form multiple industries that may still be in the growth phase but have potential and promise for development. The application of AM in the construction industry is profound and revolutionary and will produce profound changes in the supply chain, differentiating it from traditional construction models and supply chains.

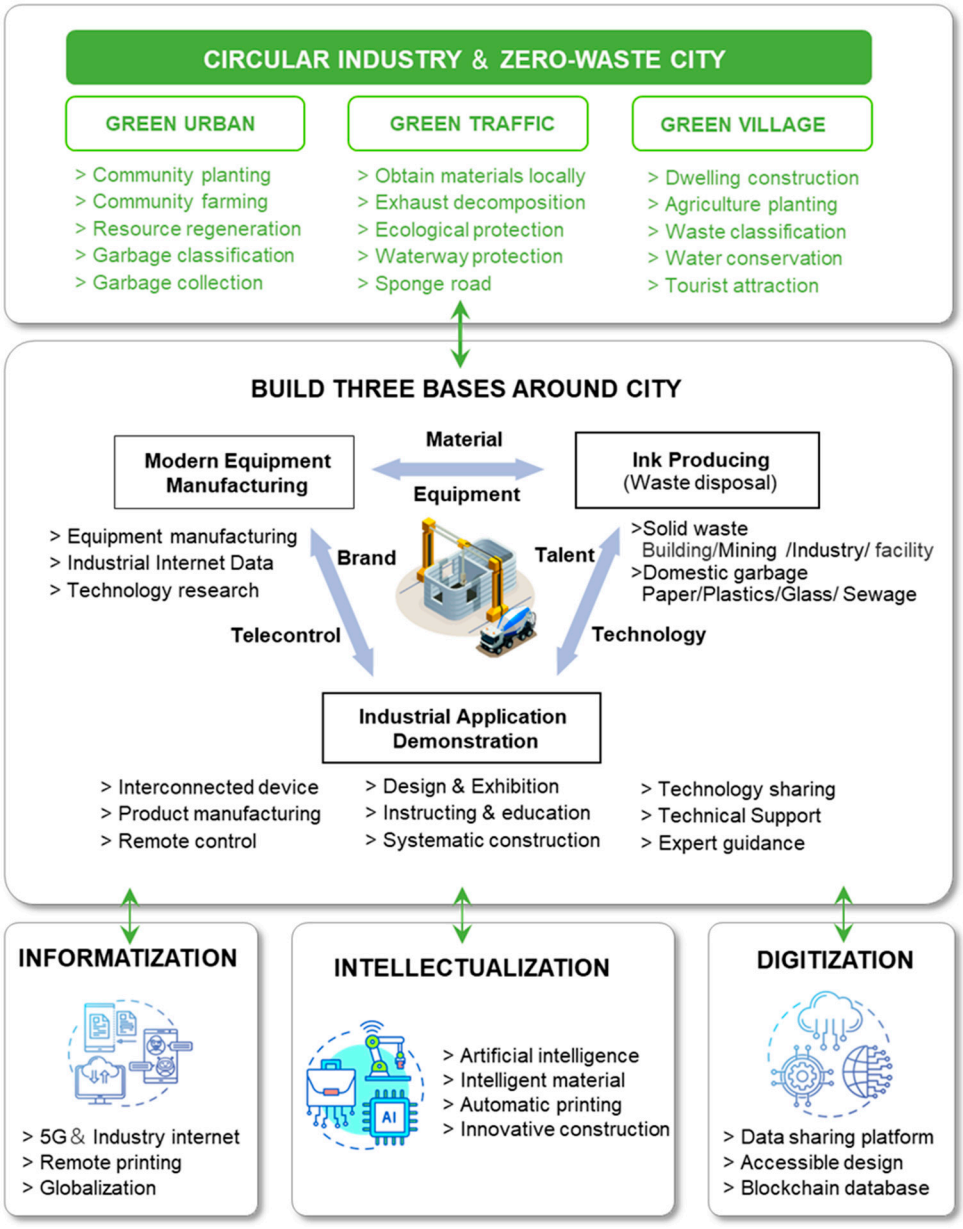


Figure 2. Green construction industry based on AM technology.

4. Case Analysis

After an in-depth study of the application of AM in the construction industry, the supply chain of YC's AM construction industry was studied. Next, the supply chain construction and analysis will be further focused on this enterprise

4.1. AM Construction Enterprise Supply Chain Substance

Figure 2 illustrates the impact of the AM architecture industry chain on the supply chain from an academic perspective. Additionally, Figure 2 introduces YC's AM architecture industry chain, which shows that AM architecture application scenarios are not limited to infrastructure but also include agriculture, manufacturing, transportation, and other industries. Different industries have different specific applications of AM, forming different supply relationships, but the nodes of different supply chains intersect, such as material recycling and recycling enterprises and modern equipment manufacturing research and development enterprises. This indicates that the supply relationships such as resource conversion and transfer between some node enterprises on the supply chain of

different industries are the same. Therefore, midstream enterprises such as AM architecture manufacturers like YC strengthen the connection between different supply chains in the entire industry chain. By creating an industrial cluster centered on AM architecture, including modern equipment manufacturing bases, material recycling and recycling bases, and industrial application demonstration bases, it optimizes the technical and economic relations between different industries and seeks the maximum benefit of the entire industry chain. The impact on the supply chain is core-shifted to the AM architecture manufacturer YC, with an overall decrease in supply chain costs and an increase in supply efficiency.

Moreover, it is discovered from the industrial chain that the number of upstream industries has decreased, such as those of steel, cement, brick and tile, building ceramics, glass, aluminum, wood, and other industries. These industries are all industries with excess production capacity in China, with fierce competition and low industry profitability. The application of AM technology in the construction industry has accelerated the elimination of backward production capacity. Through material recycling and a small number of suppliers for raw material supply, the building materials industry has greatly reduced in scale, and the number of enterprises has decreased significantly. Material recycling and recycling will account for the majority of logistics costs. The impact on the supply chain is reducing the input price of construction enterprises, increasing the profits of AM architecture manufacturers such as YC, and reducing the overall production cost of the construction industry.

Therefore, we establish an AM building supply chain structure chart in Figure 3. In Figure 3, there are no building material industry enterprises in the supply chain, and reverse logistics links multiple supply chain node enterprises. The construction subcontractor mainly focuses on basic construction, such as foundations and installations. The general contractor mainly subcontracts component manufacturing to AM architecture manufacturers, eliminating the need for other component manufacturers and construction companies. AM architecture manufacturers are involved in the design process.

As shown in the Figure 3, the supply chain consists of government departments, financial institutions, owners, designers, general contractors, AM construction manufacturers, construction subcontractors, suppliers, and supervisors. The additive manufacturer replaces the formwork manufacturer, and reverse logistics reconnects the downstream and upstream of the supply chain. In AM construction, only a small proportion of raw materials originate from suppliers. The majority of raw materials come from waste recycled by owners, construction sites, and factories, and become ink materials after processing. The improvement and development of reverse logistics is an important driver for the promotion and development of AM construction [33].

Customers and AM producers are involved in the design, and builders, suppliers, and developers are involved in the supply of raw materials. The activities in the supply chain become more diverse and complex, and the roles and functions of the participants change, resulting in a supply chain with the AM building manufacturer at its core. When the scale of a building project is small (a mobile house, shelter, isolation house, etc.) there is no need for a general contractor, and the AM building manufacturer acts as the general contractor. Unlike assembly construction, this production method is centralized and bespoke. Production and construction are combined into one process, making it suitable for customized production and the manufacture of complex components.

Due to the production characteristics of AM buildings which may lead to a reduced number of suppliers, there is less pressure on component transportation and inventory. The participants in the supply chain are more likely to form long-lasting and ongoing relationships due to the complexity of the printing process, material ratios, and waste disposal, and the AM building producer needs to manage the design, raw materials, waste recycling and disposal, printing, construction, and sales in an integrated manner [34].

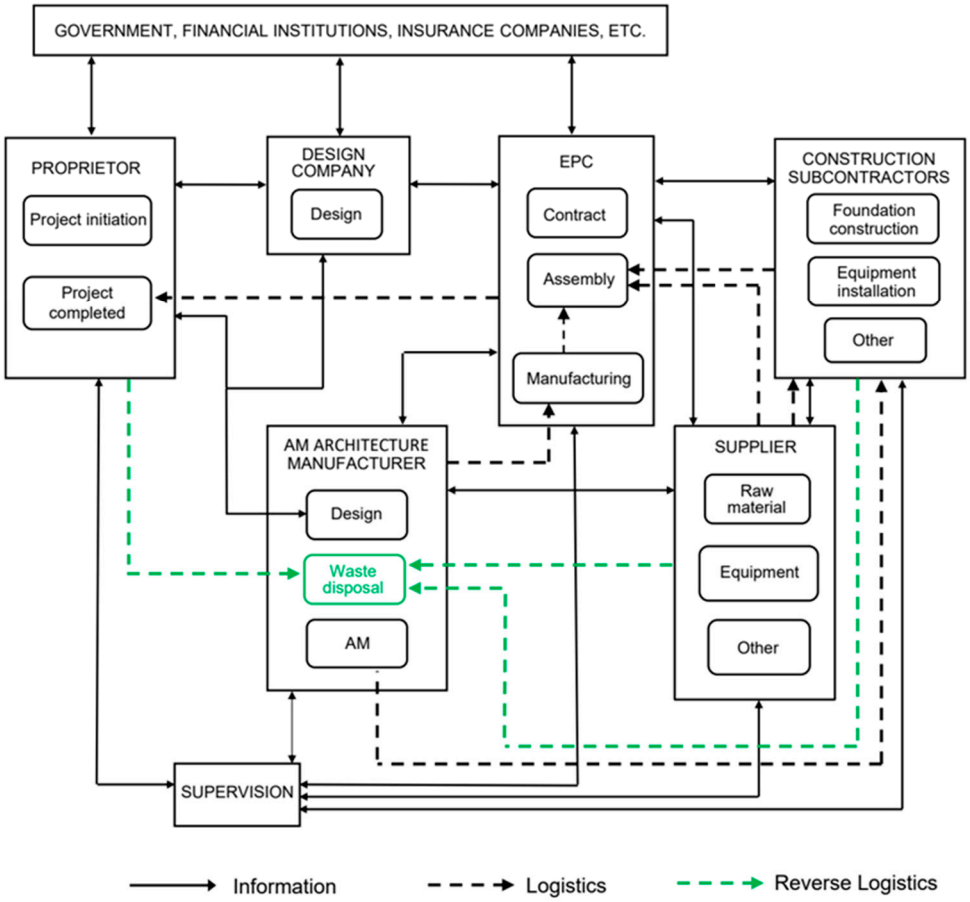


Figure 3. AM architecture supply chain model.

4.2. Supply Chain Model and Resilience Evaluation Index System

There is relatively little research on evaluation metrics for AM construction supply chains [35]. The reference documents are mainly from studies on the traditional construction industry and manufacturing supply chains. In establishing the SCR evaluation indicator system, the evaluation indicator system is established from the perspective of the entire life cycle of AM buildings, taking into account the case and the impact of the industrial chain on the supply chain in the previous section.

This article applies grounded theory to analyze and identify the factors that influence the resilience of AM building supply chains. Grounded theory is a method of establishing substantive theory from the bottom up and has a wide range of practical experience and mature coding processes, making it suitable for researching the resilience of AM building supply chains, which lacks quantitative analysis and has not yet formed a complete and mature theoretical system.

Firstly, a total of 31 articles were searched in the SCOPUS and WOS databases using keywords such as "Resilience of AM building supply chain", "Factors influencing the interruption risk of AM buildings", "Risk resistance of AM buildings", and "AM buildings". After excluding 10 articles that were not highly relevant to this study, the remaining 21 articles were studied. Deep expert interviews were also conducted, inviting relevant personnel with at least two years of work experience from general contractors, design units, supervision units, government agencies, developers, construction subcontractors, AM building and component manufacturers, and material suppliers, as well as experts who have long been engaged in research in this field in scientific research institutions or universities with rich theoretical and practical experience. The backgrounds of and information on the experts are shown in Table 1.

Table 1. Expert information.

Background	Background	Number	Percentage (%)
Age	20–30	5	17.86
	30–40	11	39.29
	40–50	7	25.00
	>50	5	17.86
Qualification	Associate	5	17.86
	Graduate	14	50.00
	Postgraduate or above	9	32.14
Status	Staff	6	21.43
	Managers	7	25.00
	Technician	5	17.86
	Executive	5	17.86
	Scholar	5	17.86
Enterprise	Supervisor	3	10.71
	Construction	4	14.29
	Am	5	17.86
	Contractor	3	10.71
	Design	3	10.71
	Logistics	3	10.71
	Logistics	7	25.00
Interview form	Interview form	6	21.43
	Video conference	18	64.29
	Email	4	14.29

Due to space constraints, this paper will not display the specific operational process of grounded theory. After a three-level coding analysis, seven dimensions and twenty-one influencing factors were identified, and the corresponding conceptual explanations for subcategories were provided, as shown in the Figure 4 and Table 2.

Table 2. Index interpretation.

Index	Interpretation
F_{11}	Ability to meet individual customer needs and solve problems innovatively
F_{12}	Whether the design of each segment corresponds to the demand and environment
F_{21}	Ability to develop innovative designs and topology optimization for buildings
F_{22}	Quality, usability, and aesthetics of AM buildings, print speed, and cost
F_{23}	Management capabilities for design, recycling, AM, construction, logistics, etc.
F_{24}	Flexible production and the ability to absorb bursts of orders
F_{31}	Reverse logistics responsiveness, efficiency, and automation
F_{32}	Optimize and adjust strategy accurately and timely according to variation
F_{41}	Ability to select and manage subcontractors and partner companies
F_{42}	Economic power and stability; relationship with local authorities and institutions
F_{43}	The system and ability to cultivate construction talents
F_{44}	Supply chain management and technological innovation capability
F_{51}	Acceptance criteria and relevant laws and regulations for AM buildings
F_{61}	The types and quantities of raw materials from different sources can meet demand; information on supply and demand is communicated accurately and quickly
F_{62}	Transportation, order demand, and production management in supply chain
F_{63}	Share risks and benefits with a common goal of synergy between the partners
F_{64}	Number of all businesses involved in supply chain operations
F_{65}	The ability to share information between participants in the supply chain
F_{66}	Ability to anticipate demand and risk; risk management and crisis awareness
F_{71}	Quality and efficiency of construction and assembly on site
F_{72}	Management capabilities for waste, staff, materials, equipment, and construction

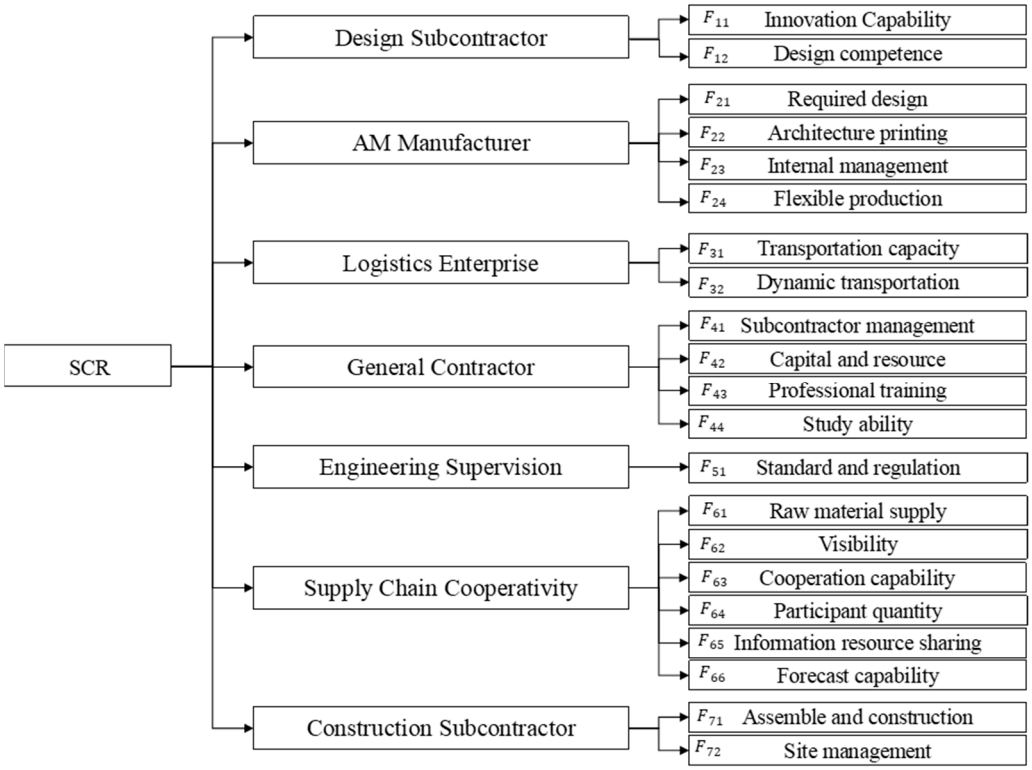


Figure 4. Evaluation index system of SCR impact factors.

5. Indicator Evaluation Process and Analysis

5.1. IFAHP

In 1983, Laarhoven and Pedrycz [36] first proposed adding a fuzzy set to the analytic hierarchy process (AHP) to obtain the fuzzy AHP(FAHP). XU [37] also applied intuitionistic fuzzy (IF) sets to the AHP and proposed the IFAHP.

Simply put, if there exists an element α and a set Y, classical mathematics only has two possible outcomes: $\alpha \in$ Y or $\alpha \notin$ Y. However, intuitionistic fuzzy sets introduce two concepts—membership functions and hesitation degrees. Membership functions are divided into a membership degree and a non-membership degree. Intuitionistic fuzzy sets can be used to represent that element α "has about 60–70% proportion" belonging to set Y, i.e., (0.6,0.3), where 0.6 is the membership degree, 0.3 is the non-membership degree, and the hesitation degree is 0.1, representing the degree to which the decision-maker believes that element α belongs to Y. Information represented by intuitionistic fuzzy numbers can better describe the fuzziness and uncertainty of evaluations, making evaluations and decisions more efficient and straightforward.

AHP is generally used to calculate index weights and performance [38]. The traditional AHP relies excessively on the subjectivity of experts. When indexes are numerous and diverse, quantifying the evaluation results becomes biased and difficult, leading to the loss of decision-making information [39]. Our index system is divided into 7 first-level and 21 s-level indexes, which require a method that can completely and objectively reflect the uncertainty and ambiguity of the evaluation [40].

In addition, considering the current situation of the AM construction industry, which is still in the stage of exploration and development, the understanding and assessment of AM architecture is vaguer. Therefore, it was decided to use IF values to describe the information of the expert evaluation and use IFAHP to determine the weight of each influencing factor to identify the critical influencing factors. This method can more objectively and comprehensively describe the uncertainty and fuzziness of decision-makers' evaluations.

5.2. Calculate Weights

Assuming IF is the judgment matrix, i and j mean rows and columns, respectively. $\mu_{ij}(0 \leq \mu_{ij} \leq 1)$ means the membership degree, which indicates the possibility that the influence degree of the ith factor is greater than that of the jth factor; $\nu_{ij}(0 \leq \nu_{ij} \leq 1)$ means the non-membership degree, which suggests the possibility that the influence degree of the ith factor is less than that of the jth factor; and $\pi_{ij}(\pi_{ij} = 1 - \mu_{ij} - \nu_{ij})$ means the hesitancy degree, which indicates the uncertainty and fuzzy degree of the expert evaluation [41].

STEP 1. Construct the IF judgment matrix.

The potential of AM in the construction industry lies not only in the designing but also in the evaluation index system for AM architecture SCR influence factors, as shown in Table 1. The relative importance of each influence factor obtained via expert scoring is expressed by the IF values, and the importance degree is judged by referring to Table 3 [42]. Firstly, comparisons are made between first-level indicators, and then the IF judgment matrix R is established. Secondly, comparisons are made between the first-level indicators in each second level to obtain six matrices (the index of construction supervision has only one second-level index, so the matrix is neglected), giving a total of seven matrices.

Table 3. Transformation relationships between qualitative indicators and IF values.

Index Value	IF Value
Extremely poor	(0.05, 0.95, 0.00)
Very poor	(0.15, 0.80, 0.05)
Poor	(0.25, 0.65, 0.10)
Medium poor	(0.35, 0.55, 0.10)
Medium	(0.50, 0.40, 0.10)
Medium good	(0.65, 0.25, 0.10)
Good	(0.75, 0.15, 0.10)
Very good	(0.85, 0.10, 0.05)
Extremely good	(0.95, 0.05, 0.00)

STEP 2. Consistency verification.

Substituting the matrices into Equation (1) [43], we arrive at the IF consistency matrices $\overline{R}$, $\overline{R} = (\overline{r}_{ij})_{n\times n}$, and $\overline{r}_{ij} = (\overline{\mu}_{ij}, \overline{\nu}_{ij}, \overline{\pi}_{ij})$.

$$\overline{r}_{ij} = \begin{cases} (\overline{\mu}_{ij}, \overline{\nu}_{ij}) \begin{cases} \overline{\mu}_{ij} = \dfrac{\sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \mu_{it}\mu_{tj}}}{\sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \mu_{it}\mu_{tj}} + \sqrt[j-i-1]{\prod_{t=i+1}^{j-1} (1-\nu_{it})(1-\nu_{tj})}} \\ \overline{\nu}_{ij} = \dfrac{\sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \nu_{it}\nu_{tj}}}{\sqrt[j-i-1]{\prod_{t=i+1}^{j-1} \nu_{it}\nu_{tj}} + \sqrt[j-i-1]{\prod_{t=i+1}^{j-1} (1-\nu_{it})(1-\nu_{tj})}} \end{cases} & j < i+1 \\ r_{ij} & j = i+1 \\ (\overline{\nu}_{ij}, \overline{\mu}_{ij}) & j > i+1 \end{cases} \tag{1}$$

Taking R and $\overline{R}$ into Equation (2) [44], the IF information distance between R and $\overline{R}$ can then be obtained as $d(R, \widetilde{R})$. If $d(R, \widetilde{R}) < \xi$, then R satisfies the consistency verification, and we can enter step 5. If $d(R, \widetilde{R}) \geq \xi$, then go to step 4. ξ is the threshold of consistency verification, generally taken as ξ = 0.1.

$$d(R, \overline{R}) = \frac{1}{2(n-1)(n-2)} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\left| \mu_{ij} - \overline{\mu}_{ij} \right| + \left| \nu_{ij} - \overline{\nu}_{ij} \right| + \left| \pi_{ij} - \overline{\pi}_{ij} \right| \right) \tag{2}$$

STEP 3. The IF judgment matrices that are not satisfied with consistency are iterated.

Set the parameter $\sigma(0 \leq \sigma \leq 1)$ to modify the matrix. σ means the similarity degree between R and $\overline{R}$. The smaller the σ, the higher the similarity. The adjusted matrix $\widetilde{R}$ is given according to Equation (3), $\widetilde{R} = (\widetilde{r}_{ij})_{n\times n}$, and $\widetilde{r}_{ij} = (\widetilde{\mu}_{ij}, \widetilde{v}_{ij}, \widetilde{\pi}_{ij})$.

$$\widetilde{r}_{ij} = \begin{cases} \widetilde{\mu}_{ij} = \frac{(\mu_{ij})^{1-\sigma}(\overline{\mu}_{ij})^{\sigma}}{(\mu_{ij})^{1-\sigma}(\overline{\mu}_{ij})^{\sigma}+(1-\mu_{ij})^{1-\sigma}(1-\overline{\mu}_{ij})^{\sigma}} \\ \widetilde{v}_{ij} = \frac{(v_{ij})^{1-\sigma}(\overline{v}_{ij})^{\sigma}}{(v_{ij})^{1-\sigma}(\overline{v}_{ij})^{\sigma}+(1-v_{ij})^{1-\sigma}(1-\overline{v}_{ij})^{\sigma}} \end{cases} \tag{3}$$

Then, the consistency verification is performed again using Equation (4) [45]. If $d(R, \widetilde{R}) < 0.1$, then satisfy the consistency verification, and go to step 5; otherwise, continue to iterate.

$$d(R, \widetilde{R}) = \frac{1}{2(n-1)(n-2)} \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\left| \mu_{ij} - \widetilde{\mu}_{ij} \right| + \left| v_{ij} - \widetilde{v}_{ij} \right| + \left| \pi_{ij} - \widetilde{\pi}_{ij} \right| \right) \tag{4}$$

STEP 4. Calculate the weights of the indexes.

The matrices that pass the consistency verification are substituted into Equation (5) [46] to calculate the weight (W_i) of each index for the previous layer.

$$W_i = \left[\frac{\sum_{j=1}^{n} \mu_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} (1 - v_{ij})}, 1 - \frac{\sum_{j=1}^{n} (1 - v_{ij})}{\sum_{i=1}^{n} \sum_{j=1}^{n} \mu_{ij}} \right] \tag{5}$$

STEP 5. By substituting the calculated weight into the IF value Algorithm (6) [47], it is found that the combination weight is equal to $F_N \otimes F_M$. F_N indicates the IF values of first-level indexes, and F_M indicates the IF values of second-level indexes.

$$F_N \otimes F_M = (\mu_{F_N} \cdot \mu_{F_M}, v_{F_N} + v_{F_M} - v_{F_N} \cdot v_{F_M}) \tag{6}$$

STEP 6. Calculate and rank the index scores.

In AHP, the combination weight directly determines the degree of importance. However, in IFAHP, the combination weight includes the membership, non-membership, and hesitancy degrees, and the direct ranking of the membership degrees of all indexes ignores the intrinsic connections between them. The evaluation result should consider complete information. After comparing the existing score functions, in order to be able to comprehensively consider the membership, non-membership, and hesitation degrees and obtain an acceptable ranking result, the method is finally chosen in this paper.

For $F_i = (\mu_{F_i}, v_{F_i}, \pi_{F_i})$ and $F_j = (\mu_{F_j}, v_{F_j}, \pi_{F_j})$, their scores can be obtained by substituting their IF values into the following equation [48].

$$S(F) = \frac{1 - v_F}{1 + \pi_F} \begin{cases} F_i > F_j & S(F_i) > S(F_j) \\ F_i < F_j & S(F_i) < S(F_j) \\ A(F) = \begin{cases} F_i > F_j, A(F_i) > A(F_j) \\ F_i > F_j, A(F_i) < A(F_j) \\ F_i = F_j, A(F_i) = A(F_j) \end{cases} & S(F_i) = S(F_j) \end{cases} \tag{7}$$

A larger $S(F)$ indicates a greater degree of influence, and if there is the same score, the accuracy function $A(F)$ of the IF values should be calculated. A larger $A(F)$ indicates a greater degree of influence Taking the accuracy function into the score function, the score function formula can then be expanded as Equation (7).

This method integrates the influences of the membership, non-membership, and hesitancy degrees on the score and is able to calculate the score of each index and rank their importance and finally obtain the critical influencing factors.

6. Empirical Analysis

After the identification of the influencing factors is completed, this study selected five senior professionals in the AM construction supply chain field as the weight and empirical research experts for this study. Most of these experts have more than 5 years of industry experience and are middle to high-level managers with extensive experience in AM construction supply chain management. One of them is from Company YC. The experts evaluated the relative importance of each influencing factor (comparing the degrees of impact of the seven influencing factors on the resilience of the AM construction supply chain in pairs) and expressed it using intuitionistic fuzzy numbers. The relationship between relative importance and intuitionistic fuzzy numbers is shown in Table 3. The 5 experts had equal weighting in the evaluation, and the arithmetic mean of the scores given by the experts was calculated by adding them together. The results of the scoring were expressed using IF numbers, and the weights of each indicator were calculated according to the previously given calculation steps for determining the weights.

STEP 1. The expert weights are identical, and we calculate the average of the scoring results, and seven matrices are constructed based on the outcome. The detailed results are as follows.

IF preference relation matrix-R_F

$$[R_F] = \begin{vmatrix} (0.50,0.50) & (0.30,0.55) & (0.40,0.45) & (0.40,0.50) & (0.35,0.55) & (0.40,0.50) & (0.40,0.50) \\ (0.55,0.30) & (0.50,0.50) & (0.55,0.35) & (0.55,0.40) & (0.50,0.45) & (0.55,0.44) & (0.50,0.30) \\ (0.45,0.40) & (0.35,0.55) & (0.50,0.50) & (0.40,0.55) & (0.40,0.50) & (0.40,0.50) & (0.43,0.41) \\ (0.50,0.40) & (0.40,0.55) & (0.55,0.40) & (0.50,0.50) & (0.40,0.50) & (0.46,0.44) & (0.50,0.40) \\ (0.55,0.35) & (0.45,0.50) & (0.50,0.40) & (0.50,0.40) & (0.50,0.50) & (0.50,0.45) & (0.50,0.40) \\ (0.50,0.40) & (0.44,0.55) & (0.50,0.40) & (0.44,0.46) & (0.45,0.50) & (0.50,0.50) & (0.50,0.40) \\ (0.50,0.40) & (0.30,0.50) & (0.41,0.43) & (0.40,0.50) & (0.40,0.50) & (0.40,0.50) & (0.50,0.50) \end{vmatrix}$$

IF preference relation matrix-R_1

$$[R_1] = \begin{vmatrix} (0.50,0.50) & (0.55,0.40) \\ (0.40,0.55) & (0.50,0.50) \end{vmatrix}$$

IF preference relation matrix-R_2

$$[R_2] = \begin{vmatrix} (0.50,0.50) & (0.40,0.60) & (0.40,0.50) & (0.50,0.30) \\ (0.60,0.40) & (0.50,0.50) & (0.55,0.45) & (0.55,0.40) \\ (0.50,0.40) & (0.45,0.55) & (0.50,0.50) & (0.55,0.40) \\ (0.30,0.50) & (0.40,0.55) & (0.40,0.55) & (0.50,0.50) \end{vmatrix}$$

IF preference relation matrix-R_3

$$[R_3] = \begin{vmatrix} (0.50,0.50) & (0.40,0.50) \\ (0.50,0.40) & (0.50,0.50) \end{vmatrix}$$

IF preference relation matrix-R_4

$$[R_4] = \begin{vmatrix} (0.50,0.50) & (0.45,0.40) & (0.45,0.50) & (0.45,0.43) \\ (0.40,0.45) & (0.50,0.50) & (0.40,0.45) & (0.52,0.43) \\ (0.50,0.45) & (0.45,0.40) & (0.50,0.50) & (0.50,0.45) \\ (0.43,0.45) & (0.43,0.52) & (0.45,0.50) & (0.50,0.50) \end{vmatrix}$$

IF preference relation matrix-R_6

$$[R_6] = \begin{vmatrix} (0.50,0.50) & (0.45,0.40) & (0.40,0.40) & (0.50,0.35) & (0.40,0.50) & (0.45,0.40) \\ (0.40,0.45) & (0.50,0.50) & (0.45,0.40) & (0.45,0.40) & (0.40,0.50) & (0.50,0.40) \\ (0.40,0.40) & (0.40,0.45) & (0.50,0.50) & (0.45,0.40) & (0.40,0.50) & (0.45,0.40) \\ (0.35,0.50) & (0.40,0.45) & (0.40,0.45) & (0.50,0.50) & (0.40,0.55) & (0.40,0.50) \\ (0.50,0.40) & (0.50,0.40) & (0.50,0.40) & (0.55,0.40) & (0.50,0.50) & (0.50,0.40) \\ (0.40,0.45) & (0.40,0.50) & (0.40,0.45) & (0.50,0.40) & (0.40,0.50) & (0.50,0.50) \end{vmatrix}$$

IF preference relation matrix-R_7

$$[R_7] = \begin{vmatrix} (0.50,0.50) & (0.40,0.60) \\ (0.60,0.40) & (0.50,0.50) \end{vmatrix}$$

STEP 2. Substituting R_F into Equation (1) yields $\overline{R}_F$, and taking R_F and $\overline{R}_F$ into Equation(2) obtains $d(R_F, \overline{R}_F) = 0.0911 < 0.1$, and the result satisfies the consistency verification, following the same method to obtain $d(R_2, \overline{R}_2) = 0.0995$, $d(R_4, \overline{R}_4) = 0.1275$, and $d(R_6, \overline{R}_6) = 0.1151$. By substituting R_1, R_3, and R_7 into Formula (1), it is found that their IF judgment matrix is equal to the IF consistency matrices because the n of them is two, so they directly pass the consistency verification ($R_1 = \overline{R}_1$,$R_3 = \overline{R}_3$, $R_7 = \overline{R}_7$). Finally, we pass the consistency verification with $\overline{R}_F$, $\overline{R}_1$, $\overline{R}_2$, $\overline{R}_3$ and $\overline{R}_7$. The detailed results of $\overline{R}_F$ and $\overline{R}_2$ are as follows.

IF consistency judgment matrix-$\overline{R}_F$

$$[\overline{R}_F] = \begin{vmatrix} (0.5000, 0.5000) & (0.3000, 0.5500) & (0.3438, 0.3969) & (0.3255, 0.4744) & (0.3051, 0.4833) & (0.3406, 0.4699) & (0.3560, 0.3905) \\ (0.5500, 0.3000) & (0.5000, 0.5000) & (0.5500, 0.5000) & (0.4490, 0.3969) & (0.4490, 0.3747) & (0.4863, 0.3645) & (0.5200, 0.3183) \\ (0.3969, 0.3438) & (0.3500, 0.5500) & (0.5000, 0.5000) & (0.4000, 0.5500) & (0.3077, 0.5500) & (0.3809, 0.4699) & (0.4147, 0.4162) \\ (0.4744, 0.3255) & (0.3969, 0.4490) & (0.5500, 0.4000) & (0.5000, 0.5000) & (0.4000, 0.5000) & (0.4000, 0.4500) & (0.4298, 0.3714) \\ (0.4833, 0.3051) & (0.3747, 0.4490) & (0.5500, 0.3077) & (0.5000, 0.4000) & (0.5000, 0.5000) & (0.5000, 0.4500) & (0.5000, 0.3529) \\ (0.4699, 0.3406) & (0.3645, 0.4863) & (0.4699, 0.3809) & (0.4500, 0.4000) & (0.4500, 0.5000) & (0.5000, 0.5000) & (0.5000, 0.4000) \\ (0.3905, 0.3560) & (0.3183, 0.5200) & (0.4162, 0.4147) & (0.3714, 0.4298) & (0.3529, 0.5000) & (0.4000, 0.5000) & (0.5000, 0.5000) \end{vmatrix}$$

IF consistency judgment matrix-$\overline{R}_2$

$$[\overline{R}_2] = \begin{vmatrix} (0.5000, 0.5000) & (0.4000, 0.6000) & (0.4490, 0.6716) & (0.4490, 0.4495) \\ (0.6000, 0.4000) & (0.5000, 0.5000) & (0.5500, 0.4500) & (0.5990, 0.3529) \\ (0.6716, 0.4490) & (0.4500, 0.5500) & (0.5000, 0.5000) & (0.5500, 0.4000) \\ (0.4495, 0.4490) & (0.3529, 0.5990) & (0.4000, 0.5500) & (0.5000, 0.5000) \end{vmatrix}$$

STEP 3. $\overline{R}_4$ and $\overline{R}_6$ do not pass the consistency verification, so they are modified by substituting Equation (3) to obtain $d(R_4, \widetilde{R}_4) = 0.0712$ and $d(R_6, \widetilde{R}_6) = 0.06981$, which pass the consistency verification. The detailed results of $\widetilde{R}_4$ and $\widetilde{R}_6$ are as follows.

Modified IF consistency judgment matrix-$\widetilde{R}_4$

$$\left[\widetilde{R}_4\right] = \begin{vmatrix} (0.5000, 0.5000) & (0.4500, 0.4000) & (0.3908, 0.4100) & (0.4559, 0.4063) \\ (0.4000, 0.4500) & (0.5000, 0.5000) & (0.4000, 0.4500) & (0.4474, 0.4118) \\ (0.4100, 0.3908) & (0.4500, 0.4000) & (0.5000, 0.5000) & (0.5000, 0.4500) \\ (0.4063, 0.4559) & (0.4118, 0.4474) & (0.4500, 0.5000) & (0.5000, 0.5000) \end{vmatrix}$$

Modified IF consistency judgment matrix-$\widetilde{R}_6$

$$\left[\widetilde{R}_6\right] = \begin{vmatrix} (0.5000, 0.5000) & (0.4500, 0.4000) & (0.4006, 0.3433) & (0.4250, 0.3243) & (0.3713, 0.4389) & (0.4199, 0.3638) \\ (0.4000, 0.4500) & (0.5000, 0.5000) & (0.4500, 0.4000) & (0.4204, 0.3433) & (0.3715, 0.4544) & (0.4298, 0.3807) \\ (0.3433, 0.4006) & (0.4000, 0.4500) & (0.5000, 0.5000) & (0.4500, 0.4000) & (0.3715, 0.4693) & (0.4052, 0.4000) \\ (0.3243, 0.4250) & (0.3433, 0.4204) & (0.4000, 0.4500) & (0.5000, 0.5000) & (0.4000, 0.5500) & (0.4000, 0.4693) \\ (0.4389, 0.3713) & (0.4544, 0.3715) & (0.4693, 0.3715) & (0.5500, 0.4000) & (0.5000, 0.5000) & (0.5000, 0.4000) \\ (0.3638, 0.4199) & (0.3807, 0.4298) & (0.4000, 0.4052) & (0.4693, 0.4000) & (0.4000, 0.5000) & (0.5000, 0.5000) \end{vmatrix}$$

STEP 4. We substitute all the matrices that pass the consistency verification into Equation (5) to calculate the weight of each index for the previous layer. Then, the combination weights of all second-level indexes are given according to Equation (6). The combination weight of F_{11} is equal to $F_1 \otimes F_{11}$.

$F_1 \otimes F_{11}$ = (0.089, 0.824, 0.087)⊗(0.512, 0.436, 0.052) = (0.046, 0.900, 0.054). Similarly, we can obtain the combination weights of the other indexes. The weights and combination weights of all the indexes are shown in Table 4.

Table 4. The weights and combination weights of all indexes.

Weight of Index		Combination Weight
First-Level Index	**Second-Level Index**	
W_{F1}(0.089, 0.824, 0.087)	W_{F11}(0.512, 0.436, 0.052)	(0.0456, 0.9007, 0.0537)
	W_{F12}(0.439, 0.513, 0.048)	(0.0391, 0.9143, 0.0466)
W_{F2}(0.126, 0.793, 0.081)	W_{F21}(0.223, 0.775, 0.002)	(0.0281, 0.9534, 0.0185)
	W_{F22}(0.278, 0.710, 0.012)	(0.0350, 0.9400, 0.0250)
	W_{F23}(0.269, 0.717, 0.014)	(0.0339, 0.9414, 0.0247)
	W_{F24}(0.211, 0.760, 0.029)	(0.0266, 0.9503, 0.0231)
W_{F3}(0.099, 0.830, 0.071)	W_{F31}(0.429, 0.474, 0.097)	(0.0425, 0.9106, 0.0469)
	W_{F32}(0.476, 0.421, 0.103)	(0.0471, 0.9016, 0.0513)
W_{F4}(0.114, 0.811, 0.075)	W_{F41}(0.204, 0.682, 0.114)	(0.0233, 0.9399, 0.0368)
	W_{F42}(0.198, 0.695, 0.107)	(0.0226, 0.9423, 0.0351)
	W_{F43}(0.211, 0.685, 0.104)	(0.0241, 0.9404, 0.0355)
	W_{F44}(0.200, 0.708, 0.092)	(0.0228, 0.9448, 0.0324)
W_{F5}(0.123, 0.801, 0.076)	W_{F51}(1.000, 0.000, 0.000)	(0.1230, 0.8010, 0.0760)
W_{F6}(0.115, 0.812, 0.073)	W_{F61}(0.125, 0.764, 0.111)	(0.0144, 0.9556, 0.0300)
	W_{F62}(0.125, 0.775, 0.100)	(0.0144, 0.9577, 0.0279)
	W_{F63}(0.120, 0.781, 0.099)	(0.0138, 0.9588, 0.0274)
	W_{F64}(0.115, 0.793, 0.092)	(0.0132, 0.9611, 0.0257)
	W_{F65}(0.141, 0.767, 0.092)	(0.0162, 0.9562, 0.0276)
	W_{F66}(0.122, 0.783, 0.095)	(0.0140, 0.9592, 0.0268)
W_{F7}(0.099,0.822,0.079)	W_{F71}(0.450, 0.550, 0.000)	(0.0446, 0.9198, 0.0356)
	W_{F72}(0.550, 0.450, 0.000)	(0.0545, 0.9020, 0.0435)

STEP 5. Substituting the combination weights of all indexes into Equation (7), we arrive at the final score of each index.

$S(F_1) = 0.1619$, $S(F_2) = 0.1915$, $S(F_3) = 0.1587$, $S(F_4) = 0.1758$, $S(F_5) = 0.1849$, $S(F_6) = 0.1752$, $S(F_7) = 0.1650$, $S(F_2) > S(F_5) > S(F_4) > S(F_6) > S(F_7) > S(F_1) > S(F_2)$. Similarly, the scores of all second-level indexes are obtained, and the results and sorting are shown in Figure 5.

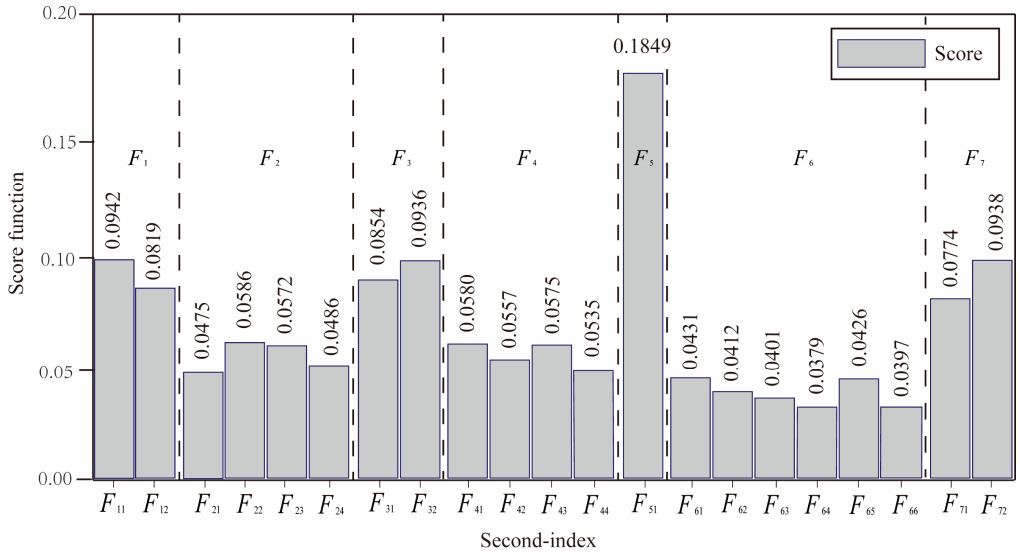


Figure 5. Histogram of secondary indicators score.

7. Results

By comparing the scores of the primary indicators, it can be concluded that the AM construction manufacturer, supervisory, general contractor, and macro factors have the most significant impacts on the resilience of the supply chain, ranking first and second, followed by the general contractors and supply chain synergy, which are ranked third and fourth. Therefore, this paper considers the factors of AM construction manufacturers and supervisory companies as the key influencing factors of the resilience of the AM construction supply chain, while general contractors and macro factors are considered as important influencing factors. Furthermore, based on the scores of the secondary indicators, the key influencing factors of each dimension are obtained.

(1) The reason for this may be that the technological threshold for AM construction is much higher than that of the traditional construction industry. The cost of equipment and materials is prohibitive. Material proportioning, digital modeling, material recovery, and the manipulation of machines require specialist engineers and technical teams, so AM building producers and products are not easily substituted and replicated and have a key impact on SCR [49]. On the other hand, AM building producers have multiple roles and functions. These include involvement in the design, waste recycling and disposal, building and formwork printing, construction, etc. AM integrates the supply chain to a certain extent. Traditionally, in the construction industry, companies in the supply chain are constantly changing, and the choice of suppliers and builders often depends on the construction site and project. However, AM construction could change this, and the supply chain would be more stable [50].

(2) Currently the most unstable factor in additive construction is the supervisory mechanism, i.e., the construction quality standards and related laws and regulations, which will profoundly affect the adoption and future of additive construction. The impact on SCR is therefore critical [51].

(3) The general contractor has the third highest degree of influence on SCR. However, the AM building manufacturer is similar to or may replace the general contractor due to functional integration. The score for the supply chain synergy is almost equal to that of a general contractor. As the construction industry becomes more digital, computerized, and intelligent, the activities of AM buildings become more complex, and the logistics and

information flows between participants in the supply chain become more frequent and complex. Information sharing and collaboration between supply chain participants will become even more important.

(4) Those with the least impact on the resilience of the supply chain are the design units, logistics companies, and construction subcontractors. The application scenarios for construction subcontractors may change due to functional integration. Original application scenarios may be replaced by AM construction producers. Logistics companies have a low impact on SCR for two main reasons. On the one hand, it is because printing on the construction site can be performed in situ without the need for inventory, unlike the huge pressure on component transport and storage in assembly construction. On the other hand, it may be that the importance of logistics is underestimated because of China's abundant labor force, low transport costs, and well-developed transport network [52].

As shown in Figure 5, the secondary indicators of important influencing factors are analyzed according to the secondary indicator score histogram.

(1) For AM building producers, building printing and internal management factors have the greatest impact on SCR. This is because the quality of the components and the building determines whether the additive building will be accepted by the market, and secondly, it is more difficult for companies to organize the various production activities including waste recycling, waste disposal, ink manufacturing, AM and building design in an efficient and orderly way.

(2) For the main contractor, the ability to manage subcontractors and the training of professionals has the greatest impact. The reason for this is the increasing number of players in the supply chain and the increasing complexity of activities. On the other hand, as the chain expands, capital and technology will continue to flow into the construction industry and supply chain, driving the development of construction technology. AM is a new technology with production methods and management tools that are very different from traditional technologies. General contractors will need to develop a large pool of talent to learn the printing, application, and management of AM buildings.

(3) Information sharing and raw material supply can seriously affect the synergy of the supply chain. The most important feature of additive construction is that it uses multiple materials for printing, and most of the materials come from waste. Raw materials come from a variety of sources. Raw material suppliers can come from all corners. Accurate and rapid responses to supply and demand are key to the functioning of the supply chain and to the widespread use of AM architecture.

(4) The secondary indicator score for logistics companies results in reverse logistics being more important than "forward logistics". "Reverse logistics" will create a huge market and have a significant impact on SCR. This will require meeting the logistical needs of raw material suppliers in changing locations and working with other supply chain participants to establish a rapid delivery mechanism for logistical needs and information.

This article's research findings have similarities to those of other studies on the impact of AM on supply chains. For instance, AM reduces the number of supply chain participants in the construction supply chain, integrates the supply chain, and affects the structure of the entire construction industry supply chain. However, the difference lies in the fact that AM has a relatively small impact on logistics in the construction industry. AM building manufacturers become the core of the supply chain, and the impact of AM on the supply chain is constructive rather than destructive in the construction industry.

8. Conclusions

Based on an in-depth analysis of the AM construction industry, this study examined an industry chain that was formed based on AM construction technology. The changes to the supply chain by the AM construction industry chain were empirically studied, and the nature of the AM construction supply chain as a closed-loop supply chain was proposed. Then, combined with the analysis of the existing literature, an evaluation index system for the resilience of the AM supply chain was established. Factors influencing SCR

were extracted from seven dimensions. IFAHP was used to analyze the weights of all the influencing factors and identify the key influencing factors.

This study shows that AM will have a dramatic effect on supply chains in the construction industry. Supply chains tend to be integrated and functionally integrated, driving the construction industry towards intelligence and information. Two indicators, the AM construction producer and the supervisory system, are key factors influencing the resilience of a supply chain. Improving the building printing and internal management of AM building manufacturers and promoting the improvement of relevant acceptance systems and laws and regulations can strengthen the supply chain, improve its resilience, and promote the development of AM buildings. This process requires the support of the whole society and universities to invest more capital and research efforts.

Although functional integration supports the integration of a supply chain and can improve the efficiency of cooperation between enterprises, it can also result in a high threshold for the AM architecture industry, with high requirements for printing materials and printing equipment. Additive construction manufacturers should strive to develop more mature, advanced, and stable printing materials and technologies. The community should work together to improve the quality and standardization of construction and to promote the exchange and sharing of AM construction technologies in order to better address supply chain risks.

The evaluation index system and the evaluation method for the resilience of an AM construction supply chain constructed in this paper are important for quantitatively assessing the impact of AM on SCR, bridging the gap in the field, and the results demonstrate the soundness of the method in this paper.

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