processes

Article

Identification of Key Brittleness Factors for the Lean–Green Manufacturing System in a Manufacturing Company in the Context of Industry 4.0, Based on the DEMATEL-ISM-MICMAC Method

Xiaoyong Zhu [1], Yu Liang [2], Yongmao Xiao [3,4,5,*], Gongwei Xiao [1] and Xiaojuan Deng [1]

1 School of Economics & Management, Shaoyang University, Shaoyang 422000, China
2 Shaoyang University Library, Shaoyang University, Shaoyang 422000, China
3 School of Computer and Information, Qiannan Normal University for Nationalities, Duyun 558000, China
4 Key Laboratory of Complex Systems and Intelligent Optimization of Guizhou Province, Duyun 558000, China
5 Key Laboratory of Complex Systems and Intelligent Optimization of Qiannan, Duyun 558000, China
* Correspondence: xym198302@163.com

Abstract: In the context of Industry 4.0, the lean–green manufacturing system has brought many advantages and challenges to industrial participants. Security is one of the main challenges encountered in the new industrial environment, because smart factory applications can easily expose the vulnerability of manufacturing and threaten the operational security of the whole system. It is difficult to address the problem of the brittleness factor in manufacturing systems. Therefore, building on vulnerability theory, this study proposes a vulnerability index system for lean–green manufacturing systems in a manufacturing company in the context of Industry 4.0. The index has four dimensions: human factors, equipment factors, environmental factors, and other factors. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach was used to calculate the degree of influence, the degree of being influenced, and the centrality and causes of the factors. The causal relationships and key influences between the factors were identified. Then, the dependence and hierarchy of each of the key influencing factors were analyzed using the Matrix-Based Cross-Impact Multiplication Applied to Classification (MICMAC) and Interpretative Structural Model (ISM) methods, and a hierarchical structural model of the factors was constructed. Finally, an intelligent manufacturing system that produces a micro-acoustic material and device was used as an example to verify the accuracy of the proposed method. The results show that the method not only identifies the key brittleness factors in a lean–green manufacturing system but can also provide a guarantee for the safe operation of a manufacturing system. This study provides theoretical guidance for the effective management of intelligent manufacturing systems; moreover, it lays a foundation and provides a new methodology for assessing the vulnerability of manufacturing systems.

Keywords: brittleness factor; lean–green manufacturing; Industry 4.0; DEMATEL-ISM-MICMAC; sustainable development

Citation: Zhu, X.; Liang, Y.; Xiao, Y.; Xiao, G.; Deng, X. Identification of Key Brittleness Factors for the Lean–Green Manufacturing System in a Manufacturing Company in the Context of Industry 4.0, Based on the DEMATEL-ISM-MICMAC Method. *Processes* **2023**, *11*, 499. https://doi.org/10.3390/pr11020499

Academic Editor: Sergey Y. Yurish

Received: 11 January 2023
Revised: 3 February 2023
Accepted: 6 February 2023
Published: 7 February 2023

1. Introduction

Manufacturing has become a key industry for creating wealth and is the basis of the material and social development of human society. With the rapid development of science and technology, the manufacturing industry in China has grown rapidly. In 2007, the total global manufacturing output was USD 9.324 trillion, and China's was USD 1.15 trillion. By 2021, China's total manufacturing output will be USD 4.864 trillion, accounting for 29.75% of the world's manufacturing added value. A strong manufacturing industry is the surest way to enhance comprehensive national power and defend national security. China's manufacturing industry has achieved remarkable results in the past 10 years through the in-depth implementation of the manufacturing power strategy; the accelerated transformation and upgrading of the manufacturing industry has led manufacturing in an intelligent, green, service-based direction, amid other transformations and upgrades. In May 2015, the State Council issued "Made in China 2025", a comprehensive overview of the implementation of the manufacturing power strategy, which aims to promote industrial and technological change and optimization. The main aspect of the strategy concerns upgrading to intelligent manufacturing, promoting a new model for the manufacturing industry model and allowing enterprise to undergo a fundamental change. In the context of Industry 4.0, smart manufacturing enterprises use modern information and communication technologies and integrate them with virtual technologies in cyberspace; this new model makes full use of the IOT information system to implement data-driven and intelligent improvement methods for manufacturing, supply and sales in traditional industries [1]. Today, Industry 4.0 has made it possible to eliminate the intermediate links between consumers and manufacturers. In addition, the high degree of digitalization, automation, and informatization has made the customization of the periphery of goods shorter and has significantly improved production efficiency, reducing labor and production costs and resulting in a significant increase in the overall production efficiency of the manufacturing industry. It is estimated that the connections and collaboration between machines and people in the Industry 4.0 production model will increase the speed of operation of the entire production system by 30% and the efficiency by 25% [2].

At the outset, Industry 4.0 was a high-tech strategic plan proposed by Germany [3]. In the era of Industry 4.0, industrial development is not the only goal; other aims include creating a modern enterprise development model based on intelligence, digitalization and personalization, continuously optimizing product quality, transforming production and service models, moving away from traditional business solutions, and improving the overall level of development of enterprise [4]. Industry 4.0 changes the relationship between the various elements of the production process; meanwhile, changes in management philosophy and management technology work together to drive changes in the organization of labor, such as in the integration of digital manufacturing technologies with advanced lean management technology, i.e., the integration of lean management with Industry 4.0. The result of the convergence of lean management and Industry 4.0 is an adaptive process of advanced artificial intelligence working in collaboration with people [5]. Lean management facilitates the exploitation of the potential of Industry 4.0, while avoiding "automation waste" (unnecessary waste in the automation process, such as repeatedly moving machines and adjusting layouts) [6]. On the other hand, new technologies are necessary to realize the concept of lean management, to reduce the pressure on shop floor workers, and to overcome the effects and impacts of lean management [7]. This integration is known as "Lean Industry 4.0" or "Lean Automation", and its benefits are mainly clustered in the five areas of flexibility, high performance, efficiency, quality, and safety [8]. Surveys have shown that companies that have adopted the Lean Industry 4.0 production model reduce production costs by nearly 40% over a 5–10-year period [9]. However, on the other hand, manufacturing consumes a great deal of the limited resources available to human society and causes serious environmental damage through the process of transforming manufacturing resources into products, as well as in the use and disposal of products. Due to the large volume and scale of the manufacturing industry, its overall impact on the environment is significant. The question of how the manufacturing industry can reduce resource consumption and produce as little environmental pollution as possible is a pressing issue. Green manufacturing is key to solving the problem of environmental pollution in the manufacturing industry, and it is crucial to controlling the sources of environmental pollution. Green manufacturing is the essence of the sustainable development strategy of modern manufacturing. Green manufacturing is committed to developing a harmonious relationship between human technological innovation and productivity enhancement on the one hand, and the natural environment on the other, in line with the current need for sustainable development. Industry 4.0 was created to address this global challenge. Thus, Industry 4.0 is, at its core, smart, green, and humanized [10]. Industry 4.0 manufacturing companies should first replace traditional energy sources with alternative, non-traditional sources of clean energy in the production process, to alleviate the problems of energy depletion and environmental pollution. Additionally, they should produce less pollution in the production and consumption of products that can be recovered and recycled to achieve sustainable development. Industry 4.0 has many benefits and creates many opportunities for industrial players. Many organizations are developing strategies to shift toward digitalization and intelligence, and manufacturing companies are responding quickly to diverse and uncertain market demands through lean–green manufacturing systems, with the rapid manufacturing of multiple varieties and small batches of products to provide environmentally friendly goods that meet customer demands.

In the context of Industry 4.0, the lean–green system for manufacturing companies is a complex system: an organic whole that encompasses the production processes of the manufacturing industry. Industry 4.0 systems aim to realize the transformation of the manufacturing industry from informatization to wisdom through cyber-physical systems, manufacturing driven by big data, cloud platforms, the Internet of Things, and other technologies. Through the deep integration of information and physical systems, and using mobile terminal and wireless communication, a virtual network world can be realized, facilitating barrier-free communication and intelligent human–computer interactions in large complex systems [11]. The lean–green manufacturing system consists of the superposition of different participant systems, with interaction effects between these systems, and the existence of nonlinear characteristics. Brittleness is a fundamental characteristic of complex systems. At the same time, a system is in an uncertain environment, where rapid changes in the external environment can result in dramatic changes in the complexity and scale of production management. The dynamic nature of the manufacturing environment is enhanced during periods of environmental change, which are more likely to stimulate the vulnerability of the manufacturing system, threatening the operational security of the entire system. Such shifts can cause the collapse of one or several subsystems (units) in the system, with the transmission and expansion of collapse behavior leading the entire system to collapse. The brittleness of manufacturing systems can change from implicit to explicit as the complexity and scale of the system increases and as the system evolves. Once triggered, brittleness can threaten the safety of the entire system operation.

Industry 4.0 has brought many advantages and also many challenges to industrial participants. Many organizations are developing strategies to move in a digital and intelligent direction. Although intelligent manufacturing enterprises can quickly respond to the di-versified and uncertain demands of the market through lean–green manufacturing systems, and provide environmentally friendly products to meet customer needs through fast manufacturing, rapid changes in the external environment have led to significant changes in the complexity and scale of production management. The dynamic characteristics of the manufacturing environment are enhanced, which can more easily stimulate the vulnerability of manufacturing systems and threaten the operational security of the whole system. With the application and development of digitalization and intelligence, manufacturing systems are becoming larger and more complex. Although highly complex systems are robust, they are more likely to experience system fragility, which can threaten the safety of the whole system. In order to ensure the safe operation of manufacturing systems, a deeper study of system brittleness and its key causative factors is required. In complex manufacturing processes, many factors affect system brittleness; these factors are often interrelated, so it is difficult to conduct a quantitative analysis and evaluation. An objective, comprehensive, and accurate method of analysis is needed to effectively identify the key brittleness factors in the system and to ensure the essential safety of system operations. This paper constructs an improved DEMATEL-ISM-MICMAC integration method and validates it with reference to a case study of a company.

This article is structured as follows. Section 2 discusses relevant studies of manufacturing system brittleness and describes the research questions. Section 3 presents an analysis of complex system brittleness factors for lean–green manufacturing in the context of Industry 4.0. Section 4 briefly describes the methods and materials. Section 5 presents an intelligent manufacturing system for the production of a micro-acoustic material and device; this is taken as an example to verify the accuracy of the proposed method of identifying the key brittleness factors of a manufacturing system. The paper ends by summarizing the research outcomes and indicating directions for future work.

2. Related Works and Research Questions

The realization of leanness and greenness, the core concepts of Industry 4.0, requires a combination of advanced technologies. The lean–green manufacturing system, in the context of Industry 4.0, is a smart manufacturing system with vertical integration, made possible by the Internet of Things. The system is complex and changeable, and the subsystem (software) evolves quickly. In order to guarantee the safe operation of the manufacturing system, we studied system brittleness and explored the key factors related to it. The vulnerability of a manufacturing system comes from both its software and its hardware. Coding errors, process defects, system software with poorly designed interactive features, and design defects and failures in the system hardware are the root causes of a system's vulnerability. At present, research on the combination of manufacturing systems and fragility theory is still in its initial stages, and the relevant literature focuses on the following areas. Some scholars have studied the fragility of just-in-time production systems under lean manufacturing systems [12], while others have studied the opportunities and challenges of manufacturing logistics systems under dynamic uncertainty [13]. Other studies focus on the fragility of industrial networks and use software tools to build robust systems. The brittleness of industrial networks has been studied using software tools to establish robust network systems, [14] and the brittleness of the Internet of Things has been studied to establish a brittleness model for different application scenarios of manufacturing IOT [15]. Elsewhere, the brittleness of manufacturing system equipment has been studied to evaluate the performance parameter index system for the state of manufacturing system equipment [16,17]. Of course, some scholars have also investigated the effect of combination of spatial modeling and fragility theory on the fragility excitation mechanisms of manufacturing systems to assess the reliability of these systems [18]. Gao Guibing et al. proposed three different methods using a generic generating function based on state entropy; by considering the variation in performance parameters, they undertook a structural fragility assessment of mixed-flow manufacturing systems, providing a reference for the safe operation and monitoring of manufacturing systems [19–21]. The main methods used for the assessment of system fragility are empirical analysis [22], agent-based methods [23], network-based methods [24], and methods based on the dynamic properties of the system [25]. The assessment methods vary according to the researcher's field and interdisciplinarity. It can be seen that in previous studies of complex networks of manufacturing systems, the problem of identifying the key vulnerability factors of manufacturing systems and the coupling relationships between the vulnerability factors have rarely been studied. Currently, as manufacturing systems are moving towards the era of Industry 4.0/smart manufacturing, the safety of manufacturing systems is more susceptible to interference from various factors, and research on the vulnerability aspects of lean and green manufacturing systems in the context of Industry 4.0 is paying more attention. Constructing a vulnerability indicator system is a prerequisite for vulnerability evaluation, while analyzing vulnerability indicator factors is an effective way to find ways to reduce vulnerability. In this study, the vulnerability factors of the manufacturing system will be identified and the evaluation system will be constructed, while not only analyzing the correlation between the factors causing the vulnerability of the manufacturing system and the degree of influence, but also identifying the logical structure and influence mechanism between the factors.

Smart manufacturing is becoming an increasingly important trend and a core element of manufacturing development. Due to the deep integration of information technology and industrialization in contemporary society, control networks, production networks, management networks, and networked interconnections have become the norm. Production networks are increasingly integrated, and common protocols, common hardware and common software are increasingly used. As such, information security in production control systems is becoming increasingly prominent, and information security threats are becoming correspondingly complex. The security of systems is one of the main challenges faced in the new industrial environment. The security of Industry 4.0 or the Internet of Things has already been studied and discussed in a number of works [25,26]. In smart manufacturing, a new form of manufacturing, security is mainly concerned with the following four areas: (1) Network security: the use of deep integration with the Internet, the network IP, wireless networks, and flexible networking for smart manufacturing brings greater security risks. (2) Data security: open, mobile, and shared data, as well as privacy protection, are facing unprecedented threats. The diversification of business applications, such as network collaboration and personalization, has placed higher demands on application security. (3) Control security: the openness of the control environment has allowed external internet threats to penetrate the production control environment. (4) Device security: the intelligence of devices leaves production equipment and products more vulnerable to attack, which, in turn, affects normal production. The vulnerability of manufacturing systems lies in these security gaps. To ensure the normal operation of the manufacturing system, we must first ensure the security of the system; the fragility factors in a manufacturing system must be identified and considered, with a focus on the security impact factors of intelligent manufacturing systems. In summary, scholars have studied the vulnerability of manufacturing systems and provided methods and tools for preventing fragility in traditional manufacturing systems. In complex manufacturing processes, it is crucial to effectively identify, quantitatively analyze, and evaluate the key fragility factors, and the interactions and interconnections among these factors, to ensure the operational safety of manufacturing systems. However, Industry 4.0 manufacturing systems have increased in complexity and scale. The goal is to realize the transformation of the manufacturing industry from informatization to wisdom through information–physical systems at the work site; the main characteristics of these systems are interconnectivity, innovation, integration, and big data. It is difficult for traditional fragility assessment methods and tools to cope with big data, the random diversification of production information, and dynamic fluctuations in the manufacturing environment. The development of vulnerability theory has, until now, encompassed environmental, resource, social, economic, and management aspects of vulnerability, which means that the vulnerability indicator system of Industry 4.0 manufacturing system is necessarily complex. In order to build up a clearer understanding of complex systems, it is first necessary to clarify the relationship and hierarchy between the many intricate factors involved, to analyze the fragility of manufacturing systems, and to ensure the normal and safe production of the system. Therefore, it is necessary to identify the factors involved in the brittleness of lean–green manufacturing systems in a smart manufacturing/Industry 4.0 scenario, as well as elucidating the relationships between the factors. This framework addresses the following research questions:

Question 1: What are the brittleness factors of lean–green manufacturing systems in Chinese manufacturing companies in the context of Industry 4.0?

Question 2: What is the causal relationship between these factors?

Question 3: What are the key brittleness factors in the lean–green manufacturing system for Chinese manufacturing companies in the context of Industry 4.0?

Question 4: What measures need to be taken to improve the functioning of lean–green manufacturing system in Chinese manufacturing companies in the context of Industry 4.0?

In this paper, combined with vulnerability theory, a vulnerability index of lean–green manufacturing systems in manufacturing companies in the context of Industry 4.0 is established. This index has four dimensions: human factors, equipment factors, environmental factors, and other factors. The interpretative structural model (ISM) method is used to analyze the correlation relationships and influence mechanisms between these factors. The Decision-Making trial and Evaluation Laboratory (DEMATEL) is used to simplify the operation of ISM and to analyze the importance and mutual influence relationships of system factors. The Matrix-Based Cross-Impact Multiplication Applied to Classification (MICMAC) approach is used to analyze the dependence-driving relationships of system factors. Considering the subjectivity and fuzziness inherent in the process of system analysis, triangular fuzzy numbers are introduced into the DEMATEL method to construct an improved DEMATEL-ISM-MICMAC integration method, which can be effectively used to research the above proposed problem. Finally, an intelligent manufacturing system used to produce a micro-acoustic material and device is taken as a case study to verify the accuracy of the proposed method. The key brittleness factors in the lean–green manufacturing system are identified to provide a guarantee for its safe operation. This study identifies the key factors that affect the vulnerability of lean–green intelligent manufacturing systems and provides theoretical guidance for the effective management of intelligent manufacturing systems; moreover, it lays a foundation for assessing the vulnerability of manufacturing systems.

3. Analysis of Complex System Brittleness Factors for Lean–Green Manufacturing with Industry 4.0

As an inherent property of complex systems, brittleness does not disappear with the evolution of the system or due to changes in the external environment. During system operations, system brittleness, once triggered, can cause the collapse of a subsystem or unit of the system, which can lead to the collapse of other subsystems or units associated with it and, eventually, the collapse of the whole system. As a fully automated manufacturing system, a lean–green manufacturing system in the context of Industry 4.0 is susceptible to the interference of various internal and external random factors during its operation and processing. This stimulates the brittleness of the manufacturing system and produces a collapse, resulting in the stagnation of the production system and delays in fulfilling customer orders or the generation of product quality defects. The process whereby manufacturing system fragility is triggered by fragility factors, leading to system collapse, is shown in Figure 1. Figure 1 shows that the process by which system fragility is triggered and the system collapses can be divided into two parts: the implicit layer and the explicit layer. The recessive layer consists of the interrelated fragility factors that affect each other, and the system fragility events that result from each fragility factor. The upper layer is the dominant layer, and it contains the structure of the system and the fragility risk resulting from the fragility events acting on the manufacturing system. In order to ensure the normal operation of the system, without collapse, it is necessary to comprehensively analyze the factors affecting the system fragility, as well as determining the internal relationship between the influencing factors and the key factors for management and monitoring; at the same time, relevant reasonable measures must be put in place for continuous improvement.

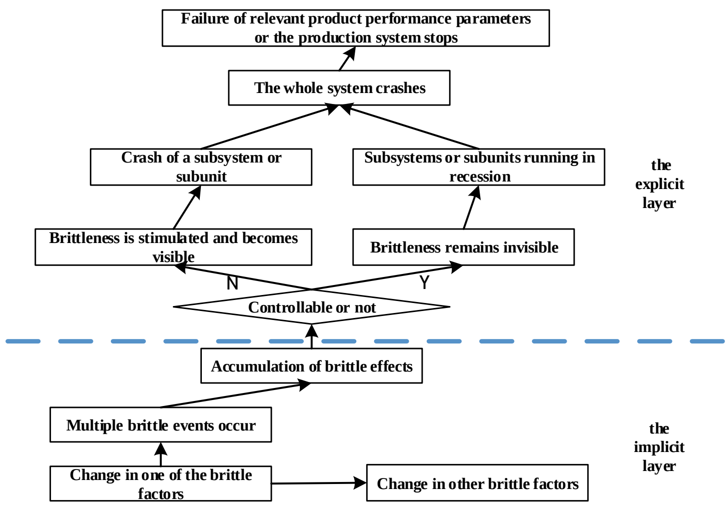

Figure 1. Analysis of the process whereby manufacturing system brittleness is stimulated until a collapse occurs.

The brittleness effect in manufacturing systems is not resolved by the improvement of these systems or changes in the external environment, and may be stimulated at any time. As such, a manufacturing system with high reliability can also be brittle; the reduction in the reliability of the manufacturing system is a manifestation of the brittleness effect [27]. Brittleness is also an inherent property of manufacturing equipment, and even highly reliable equipment is brittle [28]. When the brittleness effect accumulates to a certain degree, it will be stimulated and become visible, and the working state of the equipment unit will continuously decline, leading to the failure of the relevant performance parameters of the product output of the system. Under the cumulative effects of brittleness, the equipment may collapse, eventually performing at a lower level than the specified performance level, and stop the operation of the manufacturing system.

Lean–green manufacturing systems under Industry 4.0 are typically large complex systems. With increasing digitalization, networking, and the use of other intelligent devices, the complexity of the manufacturing environment is becoming more and more difficult to predict; meanwhile, with diverse manufacturing tasks and dynamic and uncertain external environmental perturbations, the brittleness factors that affect manufacturing systems are increasingly obscure, diverse, hazardous, and interlocking. A lean–green manufacturing system in the context of Industry 4.0 has many internal elements that are closely interconnected, and each subsystem or subunit coordinates and interconnects to accomplish the system's multitasking goals in its daily operations. Therefore, from the perspective of systems theory, we identify and analyze the factors affecting the brittleness of lean–green manufacturing systems in smart manufacturing environments. Our analysis is based on four areas: "human–machine, environment, and management". In today's manufacturing system, 5M1E (Man/Manpower, Machine, Material, Method, Measurement, Environment) analysis of manufacturing systems' operational processes, such as processing, personnel, and environmental factors, proves instructive. Brittleness in equipment units can occur due to the randomness of each manufacturing task event in the manufacturing system service process; one factor can have an impact on other factors, prompting the acceleration of brittleness in equipment units, which is reflected in the reduction of the reliability of multi-state manufacturing systems. This is the result of a combination of brittle excitation factors, which show a coupling relationship. For example, a manager's poor decision making can lead to the inefficient scheduling of processing tasks, which increases the workload of the manufacturing system's processing equipment and causes excessive wear and tear on its key functional components, thus reducing its working performance status until failure occurs [29]. To ensure the reliability and objectivity of the analyzed factors, a total of 15 experts and scholars in the field were invited to determine the causal factors of brittleness in lean–green manufacturing systems in the context of Industry 4.0. Responses were collected using a questionnaire based on the relevant literature and on the actual production context. After repeated discussions, four major categories of human factors, equipment factors, environmental factors, and other factors were identified, and 16 specific causal factors were analyzed, as shown in Table 1.

Table 1. Causal factors of brittleness in lean–green manufacturing systems in the context of Industry 4.0.

Factor Classification	No.	Brittleness Factor	Factor Classification	No.	Brittleness Factor
Human Factors	S_1	Mismanagement	Equipment factors	S_9	Software Device resilience
	S_2	Personnel intrusion		S_{10}	Line failure and repair
	S_3	Personnel operation and handling capabilities		S_{11}	Amount and status of equipment
	S_4	Personnel skills		S_{12}	Equipment processing capacity
	S_5	Personnel experience		S_{13}	Production equipment breakdown and repair
	S_6	Number of personnel	Environmental factors	S_{14}	Foreign body intrusion
Other factors	S_7	Sudden emergency orders		S_{15}	Temperature and humidity
	S_8	Inadequate emergency management system		S_{16}	Laws and regulations, etc.

(1) Human factors. The human factors that affect the brittleness of lean–green manufacturing systems in smart factories arise from human actions inside and outside the manufacturing system. The internal personnel factors of the system mainly concern the front-line personnel involved in the product manufacturing and assembly process, etc.

Compared with traditional production lines, the production line in the context of Industry 4.0 is highly automated and requires different ratios and comprehensive qualities for various types of personnel in the manufacturing system. During the operation of the automated production line, the improper management of internal personnel or the improper operation of staff are factors involved in brittleness. External factors include personnel intrusion and other related human factors. These internal and external objective conditions are the basic requirement to ensure the smooth operation of a production line, and any human factors that disturb the normal operation of the production line and production conditions will lead to the excitation of brittleness in the manufacturing system, thus producing a system collapse or a production stoppage.

(2) Equipment factors. The lean–green manufacturing system in the context of Industry 4.0 is equipment intensive and sophisticated, with a high degree of information technology, a complex production system structure, and demanding equipment operation and maintenance conditions. Automated production systems require a large number of tooling fixtures for automated rapid positioning and clamping and tooling gauges for product processing quality inspection. As the production system becomes increasingly automated, the degree of complexity of its structure affects the accuracy of product assembly and the efficiency of the production line. In the vast majority of cases, when equipment failure occurs during the operation of a manufacturing system, it leads to a brittle collapse or a forced shutdown of the production line.

(3) Environmental factors. Environmental factors are all external causes of manufacturing systems' fragility. Temperature and humidity inside smart factories, industry quality standards, and foreign object intrusion in automation systems can all lead to the initiation of manufacturing system brittleness, triggering a collapse or stoppage of the manufacturing system.

(4) Other factors. Other factors include unscheduled surge production orders, the lack of effective emergency management in the face of unforeseen events, etc. These factors can interfere with the normal operation of a manufacturing system and lead to the excitation of system brittleness, and so on.

The factors outlined in Table 1 are the specific brittle influencing factors of lean–green manufacturing systems in the context of Industry 4.0 that were ultimately identified through an extensive data review, based on the principle that certain factors have been studied more than twice by different scholars. The proposed set of influencing factors were sent to relevant experts for assessment [30–40]. These influencing factors affect each other and are coupled with each other. It is impossible to form a wholly scientific and objective understanding of the causes of the brittleness of manufacturing systems through a simple qualitative analysis; it is therefore necessary to use the corresponding mathematical models for in-depth research.

4. Research Methodology

The DEMATEL method mainly comprises graph theory and uses the matrix algorithm for constructing graphs. It is a methodology for analyzing the factors of uncertain relationships in a system on the basis of expert cognition; it is mainly used to evaluate the relationships between factors and the magnitude of their influence. In other words, DEMATEL is a method based on graph theory and matrix tools, which makes full use of experts' knowledge and experience to construct a relationship matrix for analyzing the influence relationships between system elements; it also represents these relationships with specific values. The DEMATEL method reflects not only the relationships between factors, but also the degree of action. The main purpose of the method is to study the logical relationships between the factors of influence in a complex system, so as to construct a direct influence matrix, and to accurately analyze the importance of these factors by calculating the degree of influence, the degree of cause, and the degree of centrality of each factor of influence in the whole complex system, and to determine the cause-and-effect factors.

The ISM technique is a qualitative and interpretive approach to solving complex problems by identifying the main study variables based on the complex interconnected structural mapping of the system's constituent elements. It can also help to systematically identify the solutions to complex problems with causal feedback relationships between the variables involved in the system [41]. ISM is a suitable tool for identifying the contextual relationships between these identified barriers, relying on a relationship describing the interconnection between elements, supporting the identification and ranking of complex relationships between elements in a system, and thus analyzing the influence between elements, using a systematic approach to transform unclear models into well-structured and structured models [42,43].

The MICMAC method allows for the analysis of the position and role of factors in a system, and it facilitates the assessment of the dependence and drive of factors [44,45]. The MICMAC method classifies indicators into correlated, adjusting, driving, dependent, and autonomous factors according to their roles, which can be expressed visually through the directed connecting lines of the skeleton diagram. The quadrant diagram is obtained based on the ISM reachability matrix by dividing the system into a clear hierarchy [46]. The reachable matrix with zeros and ones, ignoring the relationship between weak influencing factors in the system, offers insight into the dependency-driver role in terms of the range of influence expressed, according to strengths and weaknesses, up to a certain level of influence, and according to the value of the cumulative absoluteness of the mode of action. The ISM model was constructed to divide the factors into levels. The MICMAC method is used to analyze the influencing factors, and the position and role of the influencing factors are deeply divided. The corresponding dependencies and driving forces are determined, and targeted countermeasures are proposed. The current domestic and international literature mainly uses DEMATEL, ISM, and MICMAC alone or with two methods combined; fewer studies have combined all three methods, especially in the study of manufacturing systems [47–50]. In this paper, for the first time, three methods (DEMATEL, ISM, and MICMAC) are organically combined to form the DEMATEL-ISM-MICMAC method to study the structure of the vulnerability index system and the association between the index factors of lean–green manufacturing systems in the context of Industry 4.0. Additionally, the specific differences and mutual benefits of the organic combination of these three methods are analyzed in depth. The specific technology roadmap is shown in Figure 2. Considering that the lean–green manufacturing system in the context of Industry 4.0 has many fragile influencing factors, with strong coupling among them, the combination of DEMATEL and ISM not only helps to identify the key elements of the index system and the degree of influence, but also constructs the hierarchical structure of the index system.

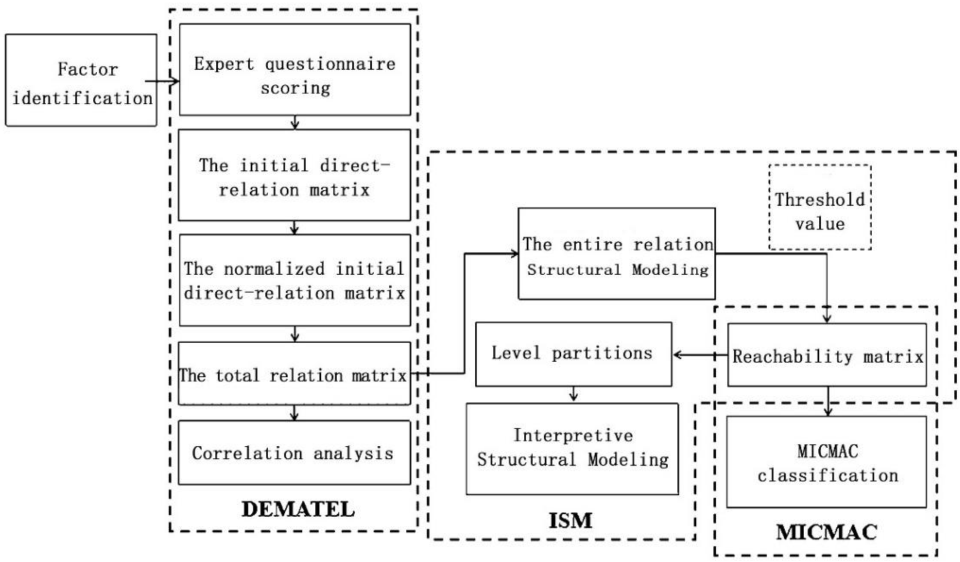

Figure 2. Method flowchart.

Since the DEMATEL method is based on expert experience for scoring, its results are influenced by individual differences and expert subjectivity, so combining fuzzy theory and the DEMATEL method can eliminate problems such as the semanticization and fuzzification of expert evaluative information. The direct influence matrix is obtained by converting the expert scores into the corresponding Triangular Fuzzy Numbers (TFNs); when fuzzified, the Triangular Fuzzy Number is converted into an accurate value using the conversion method (converting fuzzy numbers into crisp scores, CFCS) and then integrated using the ISM and MICMAC methods. The specific steps for the construction of the corresponding method-specific model are as follows.

4.1. Improved Integrated DEMATEL-ISM Method

(1) Step 1: Determine the correspondence between the linguistic variables and TFN. The results of experts' ratings of the relationships between the evaluation indicators constitute the evaluation set. The mapping relationship between the linguistic variables and fuzziness is established, as shown in Table 2.

Table 2. Semantic transformation table.

Language Variables	Triangular Fuzzy Number
No effect (NO)	(0, 0, 1)
Very low impact (VL)	(0, 1, 2)
Low impact (L)	(1, 2, 3)
High impact (H)	(2, 3, 4)
Very high impact (VH)	(3, 4, 4)

(2) Step 2: Construct the TFN direct influence matrix $Z^{(k)} = \left[\widetilde{\chi}_{ij}^{(k)}\right]_{n\times n}$ between the factors related to the vulnerability indicators of manufacturing systems, where $\widetilde{\chi}_{ij}^{(k)} = \left(a_{ij}^{k}, b_{ij}^{k}, c_{ij}^{k}\right)$ is the TFN of the k-th (k = 1, 2...., q) TFN of the degree of influence of fragility factor a with factor b, according to the expert.

(3) Step 3: the TFN of the degree of influence between the fragility factors is first standardized and its calculation formula is expressed in Equations (1)–(3).

$$l_{ij}^{k} = \frac{a_{ij}^{k} - \min\limits_{1\le k\le q} a_{ij}^{k}}{\max\limits_{1\le k\le q} c_{ij}^{k} - \min\limits_{1\le k\le q} a_{ij}^{k}} \tag{1}$$

$$m_{ij}^{k} = \frac{b_{ij}^{k} - \min\limits_{1\le k\le q} b_{ij}^{k}}{\max\limits_{1\le k\le q} c_{ij}^{k} - \min\limits_{1\le k\le q} a_{ij}^{k}} \tag{2}$$

$$r_{ij}^{k} = \frac{c_{ij}^{k} - \min\limits_{1\le k\le q} c_{ij}^{k}}{\max\limits_{1\le k\le q} c_{ij}^{k} - \min\limits_{1\le k\le q} a_{ij}^{k}} \tag{3}$$

(4) Step 4: Calculate the standardized clear value of the upper and lower boundaries of the triangular fuzzy set. Its calculation formula is expressed in (4) and (5).

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

$$v_{ij}^{k} = \frac{r_{ij}^{k}}{1 + m_{ij}^{k} - l_{ij}^{k}} \tag{5}$$

(5) Step 5: Calculate the clear value of TNF $z^{(k)}$; its calculation formula is (6):

$$z^{(k)} = \min_{1\le k\le q} a_{ij}^k + \frac{\left(\min\limits_{1\le k\le q} c_{ij}^k - \min\limits_{1\le k\le q} b_{ij}^k\right)\left(u_{ij}^k\left(1-u_{ij}^k\right)+v_{ij}^k v_{ij}^k\right)}{1-u_{ij}^k-v_{ij}^k} \tag{6}$$

(6) Step 6: Calculate the average value of $z^{(k)}$ to obtain the direct impact matrix $M = \left[z_{ij}\right]_{m\times n}$; its calculation formula is (7):

$$z_{ij} = \left(z_{ij}^1 + z_{ij}^2 + \cdots + z_{ij}^k\right)/k \tag{7}$$

(7) Step 7: The direct impact matrix is normalized to obtain the matrix $M' = \left[\chi_{ij}\right]_{m\times n}$; its calculation formula is (8):

$$M' = \frac{z_{ij}}{\max(\sum_{j=1}^{n} z_{ij})} \tag{8}$$

(8) Step 8: In order to analyze the indirect influence relationship between the factors, it is necessary to solve the integrated influence matrix M'', where I is the unit matrix. This can be found using Equation (9):

$$M'' = M' + M'^2 + \cdots + M'^n = \frac{M'(I-M'^n)}{(I-M')} = M'(I-M')^{-1} \tag{9}$$

(9) Step 9: Calculate the cause degree ($R_i - C_i$) and the center degree ($R_i + C_i$) of the driving strength between the factors that influence the fragility of the manufacturing system. From the comprehensive influence matrix $M'' = \left[t_{ij}\right]_{n\times n}$, the influence degree and the influenced degree of each factor index can be calculated as R_i and C_i, respectively (see Equation (10)); then, w deduce the centrality degree $mn = R + C$, which is used to indicate the role size (importance) of each factor in all evaluation indexes, and the cause degree $rn = R - C$, which is used to indicate the internal structure.

$$R_i = \sum\nolimits_{j=1}^{n} t_{ij} \qquad C_j = \sum\nolimits_{i=1}^{n} t_{ij} \tag{10}$$

Here, the influence degree is the sum of the elements in each row, which is the combined influence value of the corresponding element in that row on all other elements; it is referred to as the influence degree. (2) The influence degree is the sum of each element in each column, which is the combined influence value of the corresponding element in that column by all other elements; this is called the influence degree. ③ Centrality is the sum of the influence degree of each element and the influence degree is called the centrality of the element, which indicates the position of the element in the system, and the role of the size. ④ The difference between the degree of influence and the degree of being influenced of each element is the cause degree of the element. ⑤ The cause element is the cause degree > 0, which indicates that the element has a great influence on other elements; this is called the cause element. ⑥ The result element is the cause degree < 0, which indicates that the element is influenced by other elements; this is called the result element. Through the above calculations, we can judge the degree of influence of each factor on the magnitude of the manufacturing system's brittle force, according to the factors' degree of influence and the degree of being influenced. Then, according to the central degree, we can determine the importance of each indicator in the manufacturing system's brittleness.

(10) Step 10: For the 16 influencing factors in Table 1, the inter-influence relationships among the factors were evaluated by means of questionnaires and expert scoring to initially determine the correlations between the factors. The mapped inter-influence relationships among the brittle factors can be expressed using a box plot, such as that shown in Figure 3. A binary relationship box plot is a graphical representation of the intrinsic connections between the elements within a complex system, with the corresponding letters indicate the

interrelationships between the elements. It is abbreviated as box plot diagram, which can also be referred to as a block diagram. In the box plot, A indicates that the column factors have an influence on the row factors, V indicates that the row factors have an influence on the column factors, and X indicates that the row and column factors have an influence on each other.

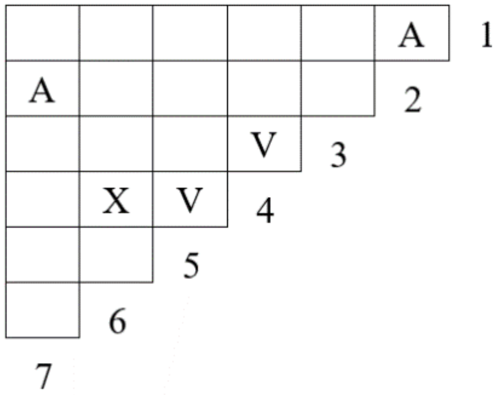

Figure 3. Box plot of the interactions between the factors.

(11) Step 11: Construct the adjacency matrix based on the interrelationship equation between the fragility factors, and, on the basis of the adjacency matrix, find the reachable matrix $H = [h_{ij}]_{n \times \mathrm{n}}$ through matrix operations.

(12) Step 12: Based on the reachable matrix, region division, level division, and skeleton matrix extraction are carried out to establish the interpretative structural model of manufacturing systems' brittle factors.

4.2. MICMAC Validation Analysis of Key Brittleness-Influencing Factors

Using the MICMAC method, quadrant diagrams are drawn according to the calculated dependency and driving force results. This enables further analysis of the status and the role played by the brittleness-influencing factors of the manufacturing system; additionally, it allows for the elucidation of different characteristics of each brittleness-influencing factor, and provides a basis for making suggestions or taking measures. The method applies the principle of matrix multiplication to analyze the degree of influence and correlation between factors by calculating their drivers and dependencies; it is often used in combination with ISM to identify factors with high dynamics and high dependencies in the system.

Stratification among indicators is performed by calculating the driving force (Q) and dependency power (Y) of each indicator, where the driving force is the sum of the elements of each row of the reachability matrix and the dependency is the sum of the elements of each column of the reachability matrix. Accordingly, the Q–Y classification diagram of influencing factors was drawn, and the mean values of drive and dependence were used as the dividing line; the diagram was finally divided into four quadrants, and quadrants I, II, III, and IV were the autonomy, dependence, association, and drive quadrants, respectively, as shown in Figure 4 [51]. Greater dependence indicates greater reliance on other factors when addressing a given factor, and greater drive indicates the extent to which this factor can help to address other factors [52]. Thus, factors in the independent quadrant are more driven and less dependent; their factors are weakly influenced by the remaining elements, but they have a greater impact on other elements. Therefore, the identification of such factors is important for assessing the brittleness of a manufacturing system and is the basis for determining whether an accidental manufacturing system collapse occurs [53].

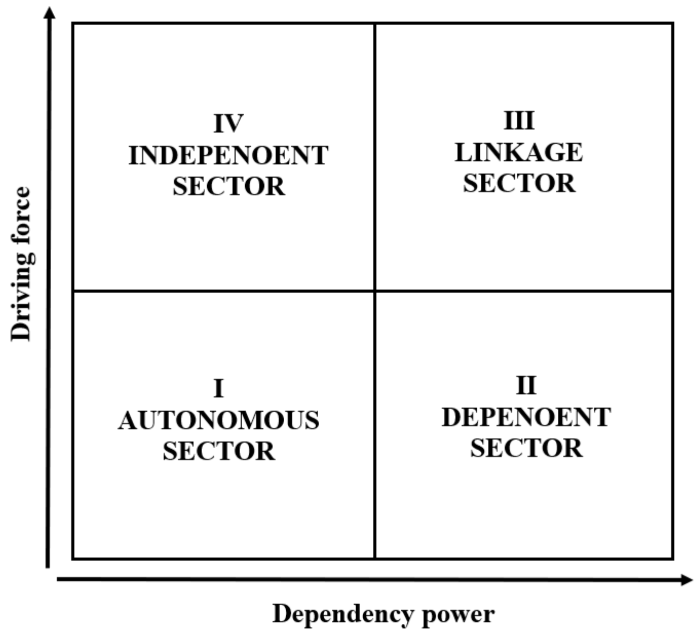

Figure 4. Matrices Impact Croises-Multiplication Appliance Classement (MICMAC).

The results of MICMAC analysis can be visualized using a two-dimensional coordinate diagram, with the vertical axis representing the driving forces and the horizontal axis representing the dependencies. For each factor in the whole complex system, the numerical magnitudes of the driving force $DF(X_i)$ and the dependency $DP(X_i)$ can be calculated based on the reachability matrix H. This can be found using Equations (11) and (12):

$$DF(X_i) = \sum_{j=1}^{n} h_{ij}(i = 1, 2, \cdots, n) \tag{11}$$

$$DP(X_i) = \sum_{i=1}^{n} h_{ij}(i = 1, 2, \cdots, n) \tag{12}$$

Based on the MICMAC analysis of the causes of brittleness in lean–green manufacturing systems in the context of Industry 4.0, a dependency matrix of indicator drivers can be derived. A dependency and driver diagram of brittleness in manufacturing systems can also be calculated, allowing for the analysis of the position and role of the influencing factors in order to suggest targeted improvements.

5. Case Study

With the goal of building a world-leading lean–green factory for the intelligent manufacturing of a micro-acoustic material and device, a smart factory proposes the following manufacturing system modules: (1) technological innovation; (2) information systems; (3) core equipment; (4) a resource strategy; and (5) basic security [54]. The technology innovation module is used to break through the key short-board equipment and to apply artificial intelligence technology, such as data mining and machine vision, to enhance the processing level, improve operation efficiency, and reduce energy consumption. The information system module integrates PDM/ERP/MES/APSWMS/SCADA and other information systems to achieve core equipment networking and monitoring, as well as the collaborative management and control of the entire production process. The core equipment module introduces and integrates dozens of core pieces of intelligent equipment, upgrades chip lines, expands packaging lines, and builds new test lines to significantly increase production capacity and automation levels. The resource strategy module upgrades the ERP system and introduces the OA system to realize the unified and collaborative management of human resources, social resources, information resources, and financial resources. The basic guarantee module, which strengthens organizational, technical, personal, mechanical, and financial factors, provides a strong guarantee for project implementation. Under the synergistic operation of each module, through carefully sorting out the process layout and material flow process, an efficient operation flow and material pulling mechanism can be established; this completely eliminates the phenomenon of material stagnation and stoppage, improves the logistic speed and production beat, and realizes lean management and the green transformation of production operations and material logistics. Through management innovations and technological innovations, and by facilitating the deep integration of information technology and industrialization technology, we will gradually generate intelligent work stations, processes, and workshops, and build a modern, intelligent factory that integrates information and industry from point to point [55].

This intelligent manufacturing system is a large and highly complex system. In order to analyze the causal factors of brittleness in this lean–green manufacturing system in the context of Industry 4.0, the pool of survey interviewers was further expanded beyond the previous 15 experts in order to assess the results more accurately and scientifically. Each of the interviewees has more than ten years of work experience; in total, 200 people were surveyed. Including enterprise staff, teachers in research institutes, and industry consultants. The job titles, work units, and education levels of the respondents are shown in Table 3.

Table 3. Distribution of respondents' basic information.

Basic Information	**Category**	**Number of People (pcs)**	**Percentage**
Work Unit	Research Institutes	40	20.0%
	Professional consulting company	22	11.0%
	Manufacturing Company	138	69.0%
Position Information	University professors	35	17.5%
	Business leaders, department managers, supervisors	30	15.0%
	General front-line employees	135	67.5%
Education level	College and below	78	39.0%
	Bachelor's degree	67	33.5%
	Masters and above	55	27.5%

The surveyed interviewers increased their basic knowledge of the company and their own expertise on the 16 brittle influencing factors of the manufacturing system described in the case study; this was achieved by applying the linguistic variables in Table 2 to the field TNF assessment. Then, according to steps 1 to 6, after defuzzification by CFCS, the direct influence matrix of the brittle influence factors of lean–green manufacturing systems in the context of Industry 4.0 was obtained, as shown in Table 4.

Table 4. Direct impact matrix of the causal factors of brittleness in lean–green manufacturing systems in the context of Industry 4.0.

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}
S_1	0	0.36	0.24	0	0	0.1	0.17	0.55	0.11	0.15	0.14	0.11	0.13	0.35	0	0
S_2	0.22	0	0	0	0	0	0.41	0.01	0	0.35	0.38	0.1	0.09	0	0	0
S_3	0	0	0	0.33	0.34	0.28	0.41	0.02	0.52	0.5	0.43	0.48	0.55	0	0	0
S_4	0	0	0	0	0.1	0	0	0	0	0	0	0.42	0	0	0	0
S_5	0	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0	0
S_6	0	0	0	0	0	0	0.23	0	0.28	0.11	0.02	0.21	0	0.45	0	0
S_7	0.01	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_8	0.33	0.35	0.18	0.2	0.01	0.29	0.29	0	0.15	0.22	0.28	0.27	0.09	0.31	0	0
S_9	0.02	0.24	0	0.03	0.01	0	0.12	0	0	0.21	0.22	0.47	0.03	0	0	0
S_{10}	0	0.09	0	0.02	0.01	0	0.1	0	0.1	0	0.31	0.13	0	0	0	0
S_{11}	0.05	0.32	0	0.31	0.13	0	0.25	0	0	0	0	0	0	0	0	0
S_{12}	0.52	0.36	0	0	0	0	0.32	0	0	0	0	0	0	0	0	0
S_{13}	0	0.19	0.23	0	0	0	0.27	0	0	0	0	0	0	0	0	0
S_{14}	0.2	0.15	0	0	0	0	0.21	0	0.21	0.57	0.18	0.32	0.01	0	0	0
S_{15}	0.07	0.11	0	0	0.17	0	0.42	0	0.45	0.52	0.38	0.59	0.29	0.31	0	0
S_{16}	0.25	0.18	0	0.06	0	0	0.41	0	0.29	0.31	0.33	0.28	0.16	0.01	0.08	0

Next, the influence, affectedness, centrality, and causality of the causal factors of brittleness in the lean–green manufacturing system are calculated according to steps 7 to 9; the results of the influence degree, influenced degree, and centrality–cause degree of each causal factor are shown in Table 5.

Table 5. Influence degree, influenced degree, centrality degree, and cause degree of each causative factor.

No.	Influence Degree	Influenced Degree	Centrality Degree	Cause Degree	No.	Influence Degree	Influenced Degree	Centrality Degree	Cause Degree
S_1	0.903	0.716	1.619	0.186	S_9	0.485	0.678	1.164	−0.193
S_2	0.538	1.020	1.558	−0.482	S_{10}	0.268	1.036	1.304	−0.769
S_3	1.299	0.243	1.542	1.057	S_{11}	0.347	1.008	1.356	−0.661
S_4	0.188	0.378	0.566	−0.191	S_{12}	0.485	1.180	1.665	−0.695
S_5	0.006	0.271	0.277	−0.264	S_{13}	0.284	0.446	0.730	−0.162
S_6	0.487	0.229	0.716	0.258	S_{14}	0.671	0.421	1.092	0.250
S_7	0.017	1.401	1.418	−1.384	S_{15}	1.007	0.000	1.188	1.147
S_8	1.152	0.256	1.409	0.896	S_{16}	0.873	0.257	1.007	1.007

According to the centrality and cause degrees, the relationships between the causal factors of the manufacturing system were plotted, as shown in Figure 5. It can be seen that the cause degrees of S_2, S_4, S_5, S_7, S_9, S_{10}, S_{11}, S_{12}, and S_{13} are negative, which means that these factors will be influenced by other factors, thus causing the manufacturing system to crash or stop. The high centrality of S_1, S_2, S_3, S_7, S_8, and S_{12} indicates that these factors are key factors in the occurrence of brittleness in manufacturing systems and need to be taken seriously by managers.

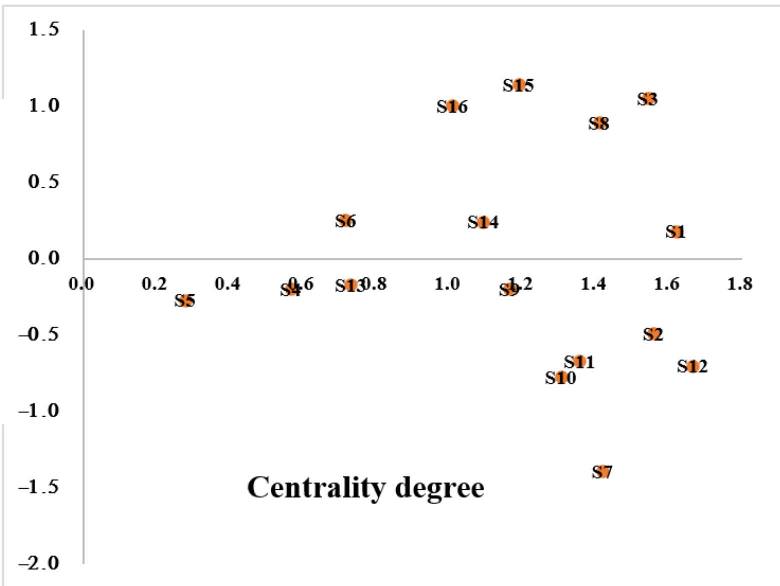

Figure 5. Centrality-Cause degree distribution of brittleness index factors in lean–green manufacturing systems in the context of Industry 4.0.

According to step 10, the 16 influencing factors detailed in Table 1 were evaluated by means of questionnaires and expert scoring, in order to initially determine the correlations between the factors and draw a variogram of the interactions among the brittle factors, as shown in Figure 6. According to step 11, the adjacency matrix was constructed based on the interrelationship equation between the brittle factors; on the basis of the adjacency matrix, the reachability matrix is obtained by matrix operations and is shown in Table 6.

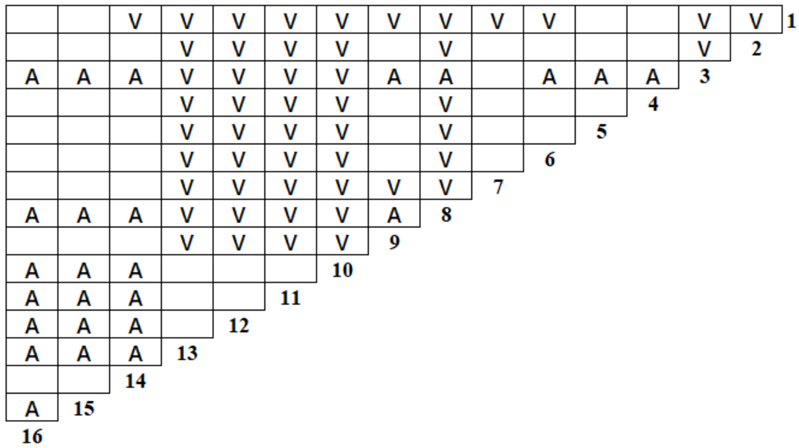

Figure 6. Box plot of the interactions between the brittleness factors of lean–green manufacturing systems in the context of Industry 4.0.

Table 6. The reachable matrix of factors influencing the brittleness of lean–green manufacturing systems in the context of Industry 4.0.

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

Based on the reachable matrix in Table 6 and Step 12, a model diagram of the ISM explanatory structure of the causal factors of brittleness is obtained, as shown in Figure 7.

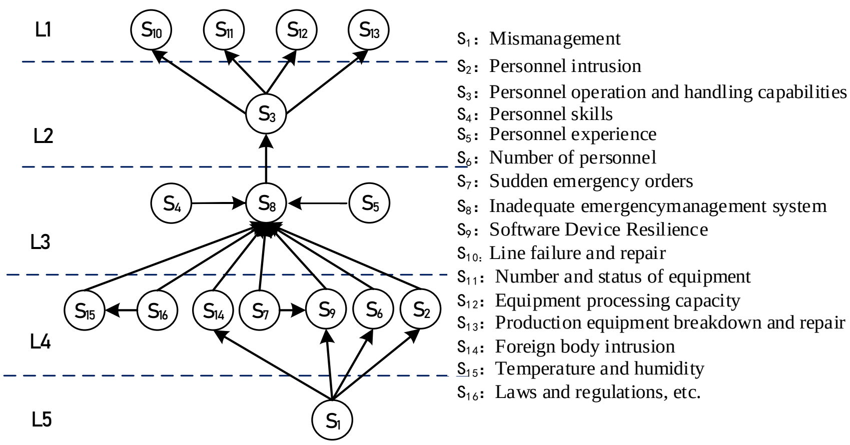

Figure 7. Multi-level recursive interpretative structural model of the brittleness of lean–green manufacturing systems in the context of Industry 4.0.

Based on the MICMAC principle and the reachability matrix *H*, the driving forces and dependencies of each factor that influences the vulnerability of the lean–green manufacturing system in the context of Industry 4.0 can be calculated, as shown in Table 7. Based on this, a driving-force-dependency power diagram of the factors influencing the fragility of the example manufacturing system is drawn, as shown in Figure 8.

Table 7. Driving-force-dependency power of factors influencing the brittleness of lean–green manufacturing systems in the context of Industry 4.0.

Factor	Dependency Power	Driving Force	Factor	Dependency Power	Driving Force
S_1	1	11	S_9	3	7
S_2	2	7	S_{10}	13	1
S_3	12	5	S_{11}	13	1
S_4	1	7	S_{12}	13	1
S_5	1	7	S_{13}	13	1
S_6	2	7	S_{14}	2	7
S_7	1	8	S_{15}	1	7
S_8	11	6	S_{16}	1	7

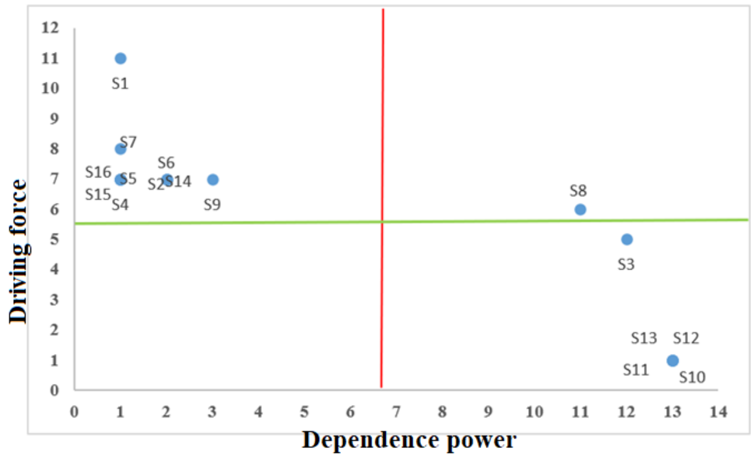

Figure 8. Driving-force-dependency power of factors influencing the brittleness of lean–green manufacturing systems in the context of Industry 4.0.

6. Discussion

6.1. Analysis of the Correlation and Importance of the Influencing Factors

The direct influence matrix *M* can be obtained according to Equations (1)–(7). According to the direct influence matrix *M* of factors that influence manufacturing systems' fragility and Equations (8)–(10), Table 5 can be obtained. Table 5 shows the influence degree, influenced degree, centrality degree, and cause degree of each causative factor of brittleness in lean–green manufacturing systems, and can be used to analyze the correlation and importance between factors. The role and importance of each factor are shown in Figure 5. The magnitude of centrality indicates the degree of association of a given factor with other factors and its importance in the system; the higher the magnitude of the value in Table 5, the more closely the factor is associated with the vulnerability indicators and the stronger the relevance; the same is true for the values situated towards the right of Figure 5. The ranking of the numerical sizes of the centrality degrees is as follows: equipment handling capacity (S_{12}), improper management (S_1), personnel intrusion (S_2), personnel operation and handling capacity (S_3), sudden emergency orders (S_7), and inadequate emergency management system (S_8). Meanwhile, there is a significant difference between the degree of influence and the degree of being influenced for temperature and humidity (S15), the improper operation of personnel (S_3), laws and regulations (S_{16}), sudden emergency orders

(S_7), equipment failure and maintenance (S_9), line failure and maintenance (S_{10}), equipment quantity and status (S_{11}), equipment handling capacity (S_{12}), and production equipment failure and maintenance (S_{13}). The first three are less strongly influenced and mainly influence the other factors, while the latter five factors are more likely to be influenced; for the rest of the factors, the degree of influence and the degree of being influenced are comparable. Among them, personnel operation and handling ability (S_3) has the greatest influence degree of 1.299, and it is the main causal factor of the excitation of manufacturing systems' brittleness leading to system collapse or stoppage, followed by temperature and humidity (S_{15}) and laws and regulations (S_{16}). Attention must also be paid to these last two factors. In terms of the roles played by different factors, the centrality degree values of mismanagement (S_1), laws and regulations (S16), and temperature and humidity (S_{15}) are relatively large and are all greater than 0. Moreover, the values for the degree of affectedness are also relatively small, indicating that these factors influence to a greater degree than they are influenced, and play a largely causative role in the system. The other factors are essentially outcome factors. From Figure 5, it can be seen that personnel operation and disposal ability (S_3), mismanagement (S_1), laws and regulations (S_{16}), and other factors are situated in the upper right part of Figure 5, meaning that their comprehensive influence on other factors is relatively large. Meanwhile, the five factors in the lower right corner are dependent factors, or passive factors; these factors are more deeply influenced by other factors and are also the direct cause of brittleness excitation.

6.2. System Hierarchy Analysis

The interpretative structure model is capable of grading factors and revealing the internal structure of a system [56]. As can be seen from the interpretative structure model, the ISM divides all factor indicators into five levels, from top to bottom, representing proximate causation (L1), transitional causation (L2, L3), deep causation (L4), and essential causation (L5). The connection between the causal factors of brittleness in lean–green manufacturing systems in the context of Industry 4.0 is highly complex, and this complexity is reflected in the following four aspects.

(1) Line failure and maintenance, equipment quantity and status, equipment handling capacity and production equipment failure, and maintenance are direct causes of system breakdown or stoppage. At the same time, the improper operation of personnel or inadequate emergency management systems are also important causes of system breakdowns. Personnel skills and experience are the factors that most directly determine the quality of a manufacturing system; they can also directly affect the productivity of production equipment and non-production equipment (software system) and the chance of equipment failure and maintenance taking place, thus affecting the scheduling of production plans and the timely completion of orders, and even lead to the collapse of the system and stop production. Most automated equipment is highly dependent on fixtures and jigs, which affects the efficiency of the production line and increases the risk of brittleness. Therefore, reducing equipment failures (including those of software systems and information systems) is one of the most important means of preventing system crashes or stoppages.

(2) Flaws in relevant personnel operations and the disposal abilities of emergency management systems are also critical. For the causal factors of the L2 and L3 layers in the ISM model, these two factors are of great importance. In particular, when an unexpected event occurs, efficient emergency response capabilities and various emergency management systems are crucial to preventing the occurrence or further spread of adverse events. Therefore, it is important to improve the business handling abilities of relevant personnel and to develop relevant contingency plans for the occurrence of an exceptional event. By utilizing the skills of relevant personnel and implementing functional emergency management systems, the probability of a system crashing or stopping can be reduced; if a crash or stop does occur, it can be controlled such that the local minimum scope of the system is maintained, or else can be resolved after a short period of time. Therefore, these

factors not only affect the efficiency of the system, but can even rectify situations where the production line goes offline.

(3) Temperature and environmental factors, such as humidity, and laws and regulations have a serious impact on the excitation of brittleness in manufacturing systems. These factors essentially belong to the L4 layer of causative factors. When these two types of factors do not meet production conditions, a manufacturing system is at high risk of brittleness. For example, if temperature and humidity conditions are not up to standard, and equipment or software information systems cannot function properly, a chain collapse phenomenon could occur in each system. The manufacturing system is certain to cease operations if one part of the product or service in the manufacturing process violates the relevant laws and regulations related to the quality standard. For instance, as a microelectronics company, the company used as a case study in this research has higher requirements for temperature and humidity; moreover, most of the connections are made in a clean and quiet workshop, which has higher requirements for humidity and temperature. Therefore, it is important to monitor such causative factors in real time and to prepare for emergencies in advance, to minimize the probability that they will violate the relevant parameters.

(4) Mismanagement is the fundamental cause of the excitation of systemic brittleness. The above-mentioned "human–machine-environment", along with the other three types of factors, can directly lead to the excitation of a system's brittleness and cause the manufacturing system to collapse or stop; however, management factors are the root cause of accidents caused by the above three types of factors. It is therefore necessary to improve the quality of managers and management systems, and to use advanced management models to establish a scientific management system, clear responsibilities, and smooth communication and feedback channels. Additionally, to achieve continuous improvement it is necessary to undertake continuous management innovation, improve the management level, and update the relevant management systems and processes.

6.3. Driving Force and Dependency Power Relationship Analysis

The dependency $DF(X_i)$ and driver $DP(X_i)$ obtained from MICMAC can be used as the x-axis and y-axis, respectively, to obtain Figure 8. On this basis, the driving force and dependency power relationship between the factors can be analyzed and classified accordingly; the relevant results can be seen from Figure 8.

Quadrant area I contains autonomous factors, which are either relatively independent and have little correlation with other factors, or are not influential enough to trigger a chain reaction; there were no factors in this category in our case study. Quadrant area II contains the dependent factors, which are generally more strongly linked to and easily controlled by other factors; however, the driving force is not strong. In this category are personnel operation and disposal ability, line failure and maintenance, equipment quantity and status, equipment handling ability, and production equipment failure and maintenance; these issues can generally be solved by first resolving other factors. Quadrant III contains the associated factors, including imperfect emergency management systems, which have high dependence and a strong driving force. Finally, quadrant IV contains the driving factors; all of the remaining 10 influencing factors fall into this category, meaning that they have a greater impact on the other factors in the system and are generally at the lower level of the ISM progression structure.

6.4. Conclusions

Based on the selection and establishment of the vulnerability indicators of lean–green manufacturing systems in the context of Industry 4.0 and the development of the implementation system, the vulnerability indicator system can be constructed from sixteen specific indicators in four major areas, namely, "human–machine, environment and management". The most important factors are generally those factors with high relevance to the other factors, and factors that play a driving role in the system; controlling these two major categories of indicators are the key to reducing a system's vulnerability. One of the most important indicators of effective manufacturing operations is the ability of manufacturing systems to meet customer needs on time, efficiently, and with high quality. However, manufacturing systems are susceptible to brittle factors that can cause them to crash or stop functioning. In order to deepen the scientific understanding of factors that cause brittleness in manufacturing systems, an improved DEMATEL-ISM-MICMAC analysis method was constructed to explore the internal connections between factors that generate fragility in lean–green manufacturing systems in the context of Industry 4.0. This study aimed to clearly determine the hierarchy of key factors and influence pathways, and to distinguish the dependency power and driving force of each fragility-influencing factor.

From the perspective of actual system in operation, the factors corresponding to the top five critical nodes in the network in terms of node importance can all be classified as related to production equipment, information transmission, and information systems, etc. As the core of system operations, the failure frequency, maintenance guarantee strategy, operation status, and recovery and processing capabilities of the equipment are the key factors affecting a system's fragility. The data indicate that these factors are also key to ensuring the safe and normal operation of the system, as is consistent with the actual operations of the system. The nodes ranked sixth and seventh in node importance correspond to the fragility factors related to work skills and work experience, respectively, indicating that the business ability of employees is also a key fragility factor that affects the normal operation of the system. As such, the comprehensive abilities of employees should be strengthened to enhance their effectiveness, and an effective job-posting assessment system should be developed to focus on the cultivation of high-quality talents and to highlight the importance of talents in the system. Additional objective and specific quantitative factors involved in the brittleness and collapse of manufacturing systems include mismanagement, industry quality standards, laws and regulations, the working system of the plant, temperature and humidity, and the operation methods and quantity of existing equipment and information systems. Although these factors have a relatively small impact on system brittleness, they are still essential to ensuring the normal operation of manufacturing systems and are important safeguards to achieving the overall function of a system. Therefore, even as managers pay increased attention to key brittleness factors, the other relevant factors should not be ignored, so that safe operation measures can be formulated more efficiently and accurately to ensure the safe and stable operation of the system.

6.5. Managerial Implications

The focus of this paper was to construct a vulnerability indicator system for lean–green manufacturing systems in the context of Industry 4.0 in Chinese manufacturing enterprises. We also aimed to analyze the relationship between various vulnerability indicator factors, establish a hierarchy of factors and classify them according to driving forces and dependencies, and finally use the proposed method to identify the key vulnerability factors that affect system fragility. For this last step, rather than considering all factors, we used a manufacturing system from an example company to identify key indicator factors and specific factors that play a role in the monitoring and management of lean–green manufacturing systems in the manufacturing industry and its enterprises. According to the relationships between the factors and the reachable pathways, an index system was built into a five-level hierarchy: from bottom to top, L5 referred to the essential causes, L4 to the deep causes, L2–3 to the transitional causes, and L1 to proximate causes. The different levels of indicators have their own status and characteristics in the system, according to which different stages of management planning can be implemented. Additionally, according to the roles of the different factors, the indicators can be divided into five categories: correlation factors, adjustment factors, driving factors, dependency factors, and autonomous factors. The roles of the factors in these categories can be visually expressed as connecting paths in the hierarchy. Based on how many paths and pointers can be managed for indicators on a primary or secondary level, managers can focus their attentions on correlation factors, adjustment factors, and driving factors, followed by dependency factors; autonomous factors do not require much attention. Based on the research presented in this paper, managers can implement different adaptive management strategies based on indicator relationships, roles, and hierarchies.

However, this study has certain limitations: the data are derived from experts' experience and scoring, and although they are authoritative and representative, they inevitably contains some degree of subjectivity and uncertainty, and may deviate from the real situation. Further refinement of the validation models can be attempted for verification. The 0 and 1 values of the ISM reachable matrix indicate that the obscure relationship is ignored, which can be corrected in the future by combining this model with fuzzy theory. At the same time, further in-depth research can be conducted based on the key fragility factors combined with the actual production situation, to enable a deeper analysis of the operation status of the equipment in the system and to develop a more reasonable maintenance guarantee strategy to guide real-world production. Additionally, to better understand the importance of each brittleness factor at a later stage of the research process, it can be measured by calculating the relevant weight classes of the factors, either by using the ANP method or the AHP method.

In addition, in order to classify the brittleness factor index system, the classification can be managed using the cluster analysis method. Manufacturing systems' brittle factor indicators can be classified as input class indicators and output class indicators, which can be analyzed using the Data Envelopment Analysis (DEA) method to determine the relevant validity of a unit. In addition, system fragility factor indicators can be ranked using the TOPSIS or VIKOR methods [57]. These multi-criteria decision-making tools can be used individually or in combination. The combined use of these methods can produce more scientific, verifiable, and robust findings.

Author Contributions: Conceptualization, X.Z., Y.L., Y.X. and G.X.; methodology, X.Z. and Y.X.; formal analysis, Y.X., X.D. and G.X.; investigation, X.Z., Y.L.; writing—original draft preparation, X.Z., Y.L., Y.X., X.D. and G.X.; writing—review and editing, X.Z., Y.L. and Y.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Hunan Province, China (Project number: 2022JJ50244); the Education Department of Hunan Province (Project number: 21B0695; 21A0475); the Project of Hunan social science achievement evaluation committee in 2022 (Project number: XSP22YBC081); the Project of Shaoyang social science achievement evaluation committee in 2022 (Project number: 22YBB10).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

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

References

1. People's Daily. 2021 Manufacturing Value Added Reached 31.4 Trillion-Yuan, Accounting for Nearly 30% of the Global Proportion of China's Comprehensive Manufacturing Strength Continues to Improve [EB/OL]. 2022. Available online: http://www.zjsjw.gov.cn/shizhengzhaibao/202208/t20220803_6639840.shtml (accessed on 18 December 2022).
2. Pfeiffer, S. *Effects of Industry 4.0 on Vocational Education and Training*; Austrian Academy of Science: Vienna, Austria, 2015; Volume 6, p. 20.
3. Li, C. Analysis of the impact of Industry 4.0 on modern equipment management. *China Equip. Eng.* **2021**, *3*, 20–21. (In Chinese)
4. Tang, L.; Huang, S. From "machine for man" to "man-machine dance"—The role of engineering talents and the shape of education in the process of Industry 4.0. *Res. High. Eng. Educ.* **2020**, *4*, 75–82. (In Chinese)
5. Dougherty, P.; Wilson, J. *Machine and Man: Accenture on the New Artificial Intelligence*; Zhao, Y., Translator; CITIC Press: Beijing, China, 2018; pp. 31–97. (In Chinese)
6. *When Lean Meets Industry 4.0: The Next Level of Operational Excellence*; The Boston Consulting Group: Boston, MA, USA, 2017; Volume 1.
7. Zuehlke, D. Smart Factory-Towards a Factory-of-things. *Annu. Rev. Control* **2010**, *34*, 129–138. [CrossRef]

8. *Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries of Productivity and Growth in Manufacturing Industries*; The Boston Consulting Group: Boston, MA, USA, 2015; Volume 2, p. 4.
9. *Five Lessons from the Frontlines of Industry 4.0*; The Boston Consulting Group: Boston, MA, USA, 2017; Volume 7.
10. Zhang, S. How Chinese manufacturing enterprises are moving towards Industry 4.0. *Mech. Des. Manuf. Eng.* **2014**, *43*, 1–5. (In Chinese)
11. Liao, G.; Yi, S.; Zhou, J.; Wen, P.; Xiong, S. Human factors and ergonomics in industry 4.0 environment. *Technol. Innov. Manag.* **2016**, *37*, 270–275. (In Chinese)
12. Albino, V.; Garavelli, A.C. A methodology for the vulnerability analysis of just-in-time production systems. *Int. J. Prod. Econ.* **1995**, *41*, 71–80. [CrossRef]
13. Nof, S.Y.; Morel, G.; Monostori, L.; Molina, A.; Filip, F. From plant and logistics control to multi-enterprise collaboration. *Annu. Rev. Control* **2006**, *30*, 55–68. [CrossRef]
14. Cheminod, M.; Bertolotti, I.C.; Durante, L.; Valenzano, A. On the analysis of vulnerability chains in industrial networks. In Proceedings of the IEEE International Workshop on Factory Communication Systems, Dresden, Germany, 21–23 May 2008; pp. 215–224.
15. DeSmit, Z.; Elhabashy, A.E.; Wells, L.J.; Camelio, J.A. An approach to cyber-physical vulnerability assessment for intelligent to cyber-physical vulnerability assessment for intelligent manufacturing systems. *J. Manuf. Syst.* **2017**, *43*, 339–351. [CrossRef]
16. Liu, W.; Xu, L.; Chen, Y. Brittle measurement and evaluation analysis of manufacturing equipment based on brittle risk entropy. *Comput. Integr. Manuf. Syst.* **2019**, *25*, 2820–2830. (In Chinese)
17. Liu, J.; Zhang, G.B.; Li, D.Y.; Li, Y.; Qian, B.M. Reliability analysis for multi-state manufacturing system based on brittleness theory. *Comput. Integr. Manuf. Syst.* **2014**, *20*, 155–164. (In Chinese)
18. Qin, Y.; Zhao, L.; Yao, Y. Quality dynamic characteristics analysis based on brittleness theory in complex manufacturing processes. *Comput. Integr. Manuf. Syst.* **2010**, *16*, 2240–2249. (In Chinese)
19. Gao, G.; Yue, W.; Zhang, R. Structural vulnerability assessment method of manufacturing systems vulnerability assessment method of manufacturing systems based on the state entropy. *Comput. Integr. Manuf. Syst.* **2017**, *23*, 134–143. (In Chinese)
20. Gao, G.; Yue, W.; Ou, W. Vulnerability assessment method for mixed-model manufacturing systems method for mixed-model manufacturing systems based on UGF. *China Mech. Eng.* **2018**, *29*, 2087–2093. (In Chinese)
21. Gao, G.; Yue, W.; Wang, F. Intelligent diagnosis on health status of manufacturing systems based on embedded CPS method and vulnerability assessment. *China Mech. Eng.* **2019**, *30*, 212–219. (In Chinese)
22. Yin, H.; Li, B.; Zhu, J.; Guo, T. Measurement method and empirical research on systemic vulnerability of environmental sustainable development capability. *Pol. J. Environ. Stud.* **2014**, *23*, 243–253.
23. Kizhakkedath, A.; Tai, K.; Sim, M.S.; Tiong, R.L.; Lin, J. *An Agent-Based Modeling and Evolutionary Optimization Approach for Vulnerability Analysis of Critical Infrastructure Networks*; Springer: Berlin/Heidelberg, Germany, 2013.
24. Cavdaroglu, B.; Hammel, E.; Mitchell, J.E.; Sharkey, T.C.; Wallace, W.A. Integrating restoration and scheduling decisions for disrupted interdependent infrastructure systems. *Ann. Oper. Res.* **2013**, *203*, 279–294. [CrossRef]
25. Krichen, M.; Lahami, M.; Cheikhrouhou, O.; Alroobaea, R.; Maâlej, A.J. *Security Testing of Internet of Things for Smart City Applications: A Formal Approach*; EAI/Springer Innovations in Communication and Computing; Springer: Cham, Switzerland, 2019; pp. 629–653. [CrossRef]
26. Jamai, I.; Ben Azzouz, L.; Saidane, L.A. Security issues in Industry 4.0. In Proceedings of the 2020 International Wireless Communications and Mobile Computing (IWCMC), Limassol, Cyprus, 15–19 June 2020; pp. 481–488. [CrossRef]
27. Ruiz-Agudelo, C.A.; Bonilla-Uribe, O.D.; Páez, C.A. The vulnerability of agricultural and livestock systems to climate variability: Using dynamic system models in the Rancheria upper basin (Sierra Nevada de Santa Marta). *J. Prot. Mt. Areas Res.* **2015**, *7*, 50–60. [CrossRef]
28. Rong, P.; Jin, H.; Wei, Q. Brittleness research on complex system based on brittle link entropy. *J. Mar. Sci. Appl.* **2006**, *5*, 51–54.
29. Xiang, R.P.; Zhang, J.H.; Qi, W.; Mei, Y.L. Research on the characteristic of complex systems based on brittle linkage. *Electr. Mach. Control.* **2005**, *9*, 111–115. (In Chinese)
30. Li, M.; Wang, W.; Zhang, Z. Study on construction risk factors based on ISM and MICMAC. *J. Saf. Environ.* **2022**, *22*, 22–28. (In Chinese) [CrossRef]
31. Wang, W.; Liu, X.; Qin, Y.; Huang, J.; Liu, Y. Assessing contributory factors in potential systemic accidents using AcciMap and integrated fuzzy ISM—MICMAC approach. *Int. J. Ind. Ergon.* **2018**, *68*, 311–326. [CrossRef]
32. Becker, T.; Meyer, M.; Windt, K. A manufacturing systems network model for the evaluation of complex manufacturing systems. *Int. J. Prod. Perform. Manag.* **2014**, *63*, 324–340. [CrossRef]
33. Vrabic, R.; Skulj, G.; Butala, P. Anomaly detection in shop floor material flow: A network theory approach. *CIRP Ann.-Manuf. Technol.* **2013**, *62*, 487–490. [CrossRef]
34. Gao, G.; Rong, T.; Yue, W. Vulnerability assessment method for the manufacturing system based on complex method for the manufacturing system based on complex network. *Comput. Integr. Manuf. Syst.* **2018**, *24*, 160–168. (In Chinese)
35. Jiang, H.; Gao, J.; Chen, F.; Gao, Z. Vulnerability analysis to distributed and complex electromechanical analysis to distributed and complex electromechanical system based on network property. *Comput. Integr. Comput. Integr. Manuf. Syst.* **2009**, *15*, 791–796. (In Chinese)

36. Li, X.; Yuan, Y.; Sun, W.; Feng, H. Bottleneck identification in job-shop based on network structure characteristic. *Comput. Integr. Manuf. Syst.* **2016**, *22*, 1088–1096. (In Chinese)
37. Li, H.; Lu, S.; Yang, T. Process route optimization of production line of complex products based on vulnerability of production line of complex products based on vulnerability analysis. *China Mech. Eng.* **2014**, *25*, 168–3173. (In Chinese)
38. Liu, W.; Xu, L. Identification of key brittleness factor for manufacturing system based on ISM and complex network. *Comput. Integr. Manuf. Syst.* **2021**, *27*, 3076–3092. (In Chinese)
39. Sun, Y.; Zhang, T.; Liu, N.; Zhao, Y.; Li, A. Analysis of the factors contributing to the late train service of high-speed railroads based on the improved ISM-DEMATEL. *Railw. Transp. Econ.* **2022**, *44*, 1–7. (In Chinese)
40. Zhang, Y.; Chen, X. Selection and analysis of vulnerability indicators for China's pelagic squid fishing based on DEMATEL-ISM-MICMAC method. *J. Shanghai Ocean. Univ.* **2022**, *2*, 479–490. (In Chinese)
41. Lee, K.H. Why and how to adopt green management into business organizations? The case study of Korean SMEs in manufacturing industry. *Manag. Decis.* **2009**, *47*, 1101–1121. [CrossRef]
42. Herron, C.; Hicks, C. The transfer of selected lean manufacturing techniques from Japanese automotive manufacturing into general manufacturing (UK) through change agents. *Robot. Comput. Manuf.* **2008**, *24*, 524–531. [CrossRef]
43. Kumar, S.; Luthra, S.; Haleem, A. Critical success factors of customer involvement in greening the supply chain: An empirical study. *Int. J. Logist. Syst. Manag.* **2014**, *19*, 283. [CrossRef]
44. Govindan, K.; Palaniappan, M.; Zhu, Q.; Kannan, D. Analysis of third party reverse logistics provider using interpretive structural modeling. *Int. J. Prod. Econ.* **2012**, *140*, 204–211. [CrossRef]
45. Kadam, S.; Bandyopadhyay, P.K. Modelling passenger interaction process (PIP) framework using ISM and MICMAC approach. *J. Rail Transp. Plan. Manag.* **2020**, *14*, 100171. [CrossRef]
46. Agarwal, R.; Shirke, A.; Panackal, N. Enablers of the collective bargaining in industrial relations: A study of India' s industrial policies through ISM and MIC.s industrial policies through ISM and MICMAC Analysis. *Indian J. Labour Econ.* **2020**, *63*, 781–798. [CrossRef]
47. Soner, O. Application of fuzzy dematel method for analyzing of accidents in enclosed spaces onboard ships. *Ocea Eng.* **2021**, *220*, 108507. [CrossRef]
48. Quiñones, R.S.; Caladcad, J.A.; Himang, C.M.; Quiñones, H.G.; Castro, C.J.; Caballes, S.A.; Abellana, D.P.; Jabilles, E.M.; Ocampo, L.A. Using Delphi and fuzzy DEMATEL for analyzing the intertwined relationships of the barriers of university technology transfer: Evidence from a developing economy. *Int. J. Innov. Stud.* **2020**, *4*, 85–104. [CrossRef]
49. Akhavan, A.; Ghatromi, A.R.; Azar, A. Mapping sustainable production model using ISM and fuzzy DEMATEl. *Ind. Manag. Stud.* **2017**, *15*, 1–26.
50. Singh, K.; Misra, M. Developing an agricultural entrepreneur inclination model for sustainable agriculture by integrating expert mining and ISM–MICMAC. *Environ. Dev. Sustain.* **2020**, *23*, 5122–5150. [CrossRef]
51. Wu, N.Z.; Xu, L. Analysis of factors influencing construction quality based on the improved explanatory structural model and cross-influence matrix multiplication. *Sci. Technol. Eng.* **2020**, *20*, 3222–3230. (In Chinese)
52. Xue, X.; Xin, C.; Xu, D.; Liu, T. Cause Analysis of Falling Accidents in Construction Engineering Based on Improved ISM-MICMAC. *J. Saf. Environment.* **2023**, 1–8. (In Chinese) [CrossRef]
53. Zhao, J.; Wang, D.; Xu, Y. Research on the Development of New Building Industrial Development Barrier Based on Fuzzy ISM-MICMAC Model. *J. Beijing Univ. J.* **2021**, *37*, 103–112. (In Chinese)
54. Ma, J.; Yao, B.; Li, Y. Smart manufacturing factory model. *Manuf. Autom.* **2019**, *41*, 24–36. (In Chinese)
55. Li, M.; Gan, N.F.; Yu, Y. Analysis of the construction of intelligent manufacturing demonstration factory. *Robot. Ind.* **2022**, *5*, 75–82. (In Chinese)
56. Virmani, N.; Sharma, V. Prioritisation and assessment of leagile manufacturing enablers using interpretive structural modelling approach. *Eur. J. Ind. Eng.* **2019**, *13*, 701. [CrossRef]
57. Opricovic, S.; Tzeng, G.-H. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *Eur. J. Oper. Res.* **2004**, *156*, 445–455. [CrossRef]