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Analysis of the LARG of the Hospital Medical Equipment Supply Chain Using the Fuzzy Inference System

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Abstract

The Lean, Agile, Resilience, and Green (LARG) supply chains are more competitive than conventional ones. Evaluating its performance under current conditions and developing suitable strategies is crucial to enhance LARG. This study aims to create an assessment model for LARG in Iran's hospital medical equipment supply chain, especially in Hamadan. The Fuzzy Inference System (FIS) evaluates LARG across four dimensions: lean, agile, resilient, and green. Key indicators obtained from a comprehensive review of the literature and other published reports in the field of LARG were also confirmed by a focused group of experts in the medical equipment supply chain field. The findings indicate that the value LARG of the medical equipment supply chain is 0.787. Key indicators for the evaluation of LARG in the hospital medical equipment supply chain include reducing overall supply chain costs, optimizing inventory management, shortening supply chain development cycle time, increasing the introduction of new products, promoting information sharing among supply chain members, establishing flexible supply bases and sourcing, reducing fossil fuel consumption, and implementing waste management practices such as reuse and recycling of recyclable materials. This research provides managers with valuable insights into the current state of LARG and serves as a reference for formulating LARG strategies and practices. The study's results enable supply chain actors, particularly in Iran's Hamadan Province, to comprehend the key indicators for improving LARG performance in the hospital medical equipment supply chain. The proposed model can be adapted to other industries and service sectors by adjusting the indicators and assessing data availability.

Keywords: Lean, Agile, Resilience, Green, LARG supply chain, Medical equipment, Hospital, Fuzzy logic, Fuzzy inference systems.

1 | Introduction

Supply chain management is pivotal in enhancing operational efficiency across various business processes. This advantage is widely applicable not only in manufacturing industries but also in service-based sectors. The

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modern market landscape is intensely competitive, demanding a delicate equilibrium between organizational profitability and the delivery of high-quality services to ensure customer satisfaction—an increasingly challenging feat for organizations to achieve. While there's a prevailing notion that supply chain concepts are exclusive to manufacturing, their implementation in this competitive environment can significantly enhance service industries' efficiency, ultimately maximizing stakeholders' contentment [1].

All Specific attention is often directed towards the healthcare industry in these discussions. This sector strives to augment the quality of care by streamlining operational processes for improved effectiveness. Presently, healthcare and medical institutions in developing countries grapple with various challenges such as customer discontent, disproportionate healthcare service expenses, insufficient service providers, inadequate medical supplies, and the absence of modern technology—a situation that necessitates the establishment of robust supply chain management systems in hospitals or healthcare units to address these concerns [2].

The supply chain within a hospital encompasses both medical and non-medical products. Medical supplies encompass clinical and pharmaceutical items like syringes, anesthesia machines, patient monitors, sterilizers, ECG machines, surgical tables, lights, and instruments. On the other hand, non-medical supplies include essentials needed for patient care, such as gowns, skeletons, bones, medical books, and administrative materials [3].

Given the relative importance of supply chain management on the one hand and the lack of awareness of service supply chain management, especially hospital supply chain management, this study focuses on private hospitals in Iran. This study addresses the primary actors in hospital supply chain management: suppliers, service providers, customers, and end consumers, who can be considered as the community/stakeholders of hospital supply chain management.

Increased societal pressure and consumer awareness of the environment have led to stringent environmental regulations, forcing companies to integrate environmental and social concerns into their management approaches [4]. As Pagell and Wu [5] state, business studies should focus on immediate economic concerns and environmental and social issues. Vachon and Klassen [6] emphasized that environmental management has evolved from an organizational focus to a supply chain perspective.

Besides enhancing organizational effectiveness, competitiveness, customer service, and profitability, supply chain management also has a critical impact on the sustainable development of a business [7].

Business sustainability involves adopting business strategies that meet the organization's current needs while simultaneously protecting and enhancing human and natural resources required in the future [8]. Implementing management methods that enhance organizational performance and overall supply chain efficiency and focus on sustainability, taking into account social, economic, and environmental concerns, is essential. Among the various supply chain management topics, supplier management for environmental and social risks and triple performance improvement (economic, social, and environmental) are crucial for ensuring supply chain sustainability [9]. Therefore, management systems are crucial and can be associated with minimal required performance. Among various supply chain management paradigms, the following are considered vital for ensuring supply chain sustainability: lean, agile, resilient, and green paradigms (referred to as the Lean, Agile, Resilience, and Green (LARG) acronym) [10].

Injection is one of the most common medical procedures performed in hospitals and healthcare centers. Needles and syringes are among the most commonly used medical tools in the healthcare industry [11]. Studies indicate that the per capita consumption of injectable drugs in Iran is approximately 11.4%, nearly four times higher than the global average [12]. Approximately 600 million syringes are used annually in Iran, highlighting the importance of the needle and syringe industry [13]. In the healthcare industry, high-quality medical equipment must be available promptly and at a reasonable cost. Moreover, medical equipment serves as hazardous medical waste and has significant environmental impacts. To compete effectively, manufacturers of medical equipment must focus on four aspects:

I. Cost reduction and quality improvement.

II. Timely and flexible delivery.

III. Effective response to market disruptions.

IV. Environmental requirements and reduction of environmental damage.

These four aspects represent the strategy of the LARG supply chain. According to research literature, evaluating supply chain performance plays a significant role in enhancing the competitiveness of the supply chain [14].

Due to the intricate nature of living systems, decision-making is often accompanied by numerous challenges, primarily when relying on incomplete, ambiguous, or inaccurate data. The Fuzzy Set (FS) theory, along with its implementation encompassing Interval-Valued Fuzzy Sets (IVFS), Intuitionistic Fuzzy Sets (IFS), Interval-Valued Intuitionistic Fuzzy Sets (IVIFS), type n-FSs, and more, offers significant tools for managing incomplete information [15].

Knowledge-based models such as Fuzzy Inference Systems (FISs) are modeling techniques that match experience and observations to the performance of a specific system to consolidate management knowledge and engineering processes. The purpose of a news system is to obtain and apply knowledge and inferential methods to achieve a more advanced solution to problems that require scientific experts to solve them. A new system consists of a scientific set including rules to reach a specific situation, an inferential tool for drawing results from scientific rules, a set of input changes to the rules, and a module for solving and correcting. An FIS, also called a fuzzy news system, consists of collections of fuzzy member functions and inference rules that use scientific rules to make inferences [16]. Therefore, a FIS combines human and fuzzy knowledge, which is used in fuzzy logic in scientific development and intelligent system design. In addition, this system uses fuzzy membership functions as scientific rules in verbal composite forms.

The research aims to address the following inquiries:

I. In what manner does the proposed fuzzy hierarchical model LARG assess the supply chain of medical equipment in hospitals?

II. Which indicators are crucial in evaluating the LARG of the medical equipment supply chain?

III. How significant is the Fuzzy Logic approach in determining whether the medical equipment supply chain is LARG, and how does it handle uncertainties during the assessment process?

IV. What are the practical implications and applications of the research findings for hospital managers and stakeholders in effectively managing the medical equipment supply chain?

Determining the best combination of LARG approaches for implementation within companies is not straightforward. There are some exchanges among paradigms. An example illustrates the presence of strategic inventory, which reduces the organization's vulnerability to unexpected events that could disrupt material supply but may mask the reasons for poor supply chain performance and create material obsolescence. Therefore, lean and green paradigms prescribe minimizing inventory levels. Utilizing measurement tools can assist managers in selecting the best combination of LARG approaches, as it enables the discovery of new ideas, methods, and processes and the identification of the highest standards of excellence [17]. It can also provide insight into the best management practices with a higher positive impact on performance.

In the literature, a set of sustainability assessment tools exists [18]. However, none have focused on the four researched paradigms. Despite the thematic relationship, there is a lack of practical indicators that allow for developing a criterion analysis for comparing lean, agility, resilience, and greenness levels in companies with the same supply chain. To address this research gap, this article presents a LARG index for assessing the degrees of lean, agility, resilience, and greenness in companies and their relevant supply chains. It also aims to continue comprehensive research in the LARG paradigms in supply chain management. This research proposes two indices: an "environmental adaptability index" for assessing greenness and resilience and an "agility index" for assessing the agility and lean nature of individual companies and their related supply chains.

These previous efforts have stimulated the need to expand research to develop measurement tools established on LARG approaches as a factor for supply chain sustainability. A tool in the form of an index to support the assessment of each level of paradigm implementation, considering the organization and the perspective of the relevant supply chain, will be proposed. Specifically, it aims to:

I. Propose a LARG index to reflect the leanness, agility, flexibility, and greenness of companies and their respective supply chains.

II. Development of a comprehensive hierarchical fuzzy model for LARG assessment of hospital medical equipment supply chain.

III. Implement the developed model for predicting and evaluating LARG of the hospital medical equipment supply chain.

IV. Demonstrate the integrated application of this index in a case study related to the medical equipment supply chain.

V. By using the proposed measurement tool, organizations can strengthen their LARG and improve the LARG of the supply chains in which they are embedded.

The article is structured as follows. After the introduction, a review of the literature on the four LARG paradigms from the perspective of supply chain management, which refers to various management approaches, is described. Subsequently, a comprehensive assessment model is proposed to evaluate the level of leanness, agility, resilience, and greenness of companies and supply chains. Furthermore, insights into the structure of the LARG index, including the description of the "system assessment method," are provided. A case study approach is developed to demonstrate the proposed application of the LARG index. Finally, some obtained results are discussed. The research's flow diagram is depicted in *Fig. 1*.

2 | Literature Review

2.1 | LARG Supply Chain Management Paradigms

For instance, in a global and integrated supply chain, timely production methods lead to more flexible and efficient distribution systems, yet, at the same time, they demand increased energy consumption. Researchers classify green logistics paradoxes into six dimensions: cost, time/flexibility, network, warehousing, and e-commerce. Recently, Carvalho et al. [19] proposed implementing LARG methods in the supply chain domain. A way to overcome these paradoxes is cost reduction, improvement in resilience and responsiveness, reliability, and reducing negative environmental impacts. Adopting LARG supply chain management methods also significantly improves the sustainability of individual companies and their relevant supply chains.

The lean approach fundamentally focuses on waste reduction as a tool for increasing real added value, meeting customer needs, and maintaining profitability [20]. Disney et al. [21] extended the lean trend to the supply chain domain. They state that lean processes create value by eliminating "wastes" in the supply chain. Several companies have successfully implemented lean principles to achieve sustainable benefits. Lean principles are implementable to ensure sustainable benefits [22]. Utilizing lean principles minimizes negative environmental effects, meaning the company is both lean and green [23]. Eliminating environmental waste through lean innovations enables the creation of business values [24]. Effective interaction between lean and sustainable efforts enables companies to avoid risks arising from non-compliance with regulatory requirements and discover new ways to improve operational and environmental performances [25].

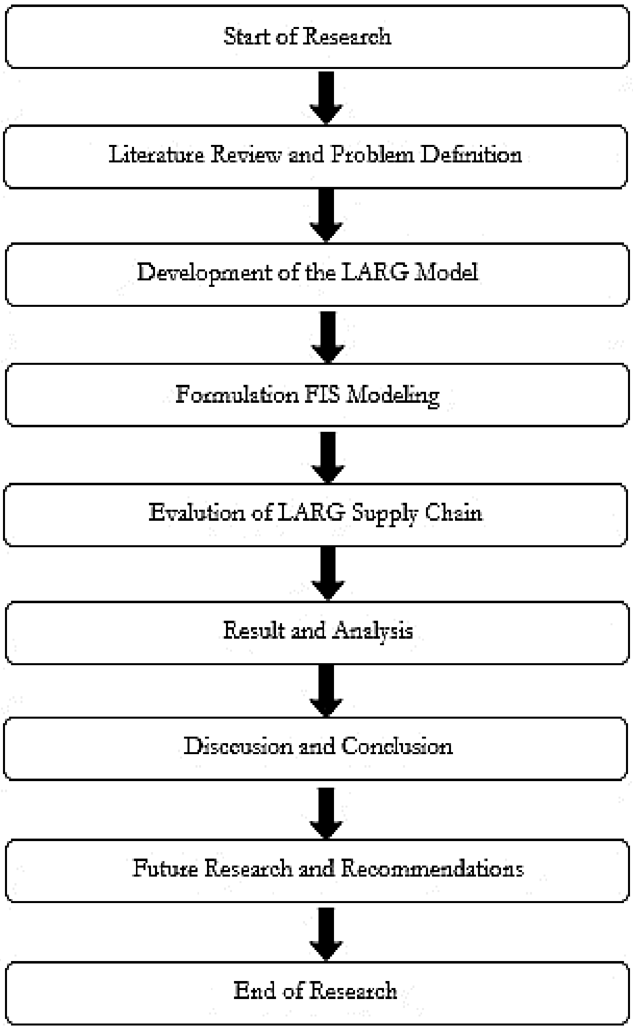

Fig. 1. Research diagram flow.

Anand and Kodali [26] also emphasize that a lean supply chain comprises integrating all upstream and downstream activities into a cohesive whole, seeking ways to more effectively handle demand fluctuations through simplification, optimization, efficiency, and asset utilization, surpassing traditional systems. Some of the lean practices in the literature include respect for people [27], customer relationships [26], quality management [28], Just-in-Time (JIT) production [29], pull production/flow [26], [28], supplier relationships [29], and error correction [30]. At the operational level, the lean paradigm uses techniques such as Kanban, 5S, visual control, cycle time, Poka-Yoke, and reducing changeover or setup times [31].

Jiang et al. [32], in their study titled "analyzing price and profit dynamics in Free Trade Port supply chains," reached a significant finding. Their research revealed that including blockchain technology notably affects sales prices within supply chains. Moreover, utilizing blockchain significantly reduces the impact of other variables on supply chain profits. Compared to supply chains that do not integrate blockchain, those adopting this technology gain substantial advantages in terms of profitability.

As customer needs continually evolve, achieving supply chain goals becomes more challenging. It involves delivering the right product in the right amount, under the right conditions, to the right place, at the right time, and cost. To overcome these conditions, Van Hauk et al. [33] propose that resilience and responsiveness in supply chain processes, networks, and their integration into other organizations need development – they must be agile. The deployment of agile methods also contributes to improved sustainability. Companies' resilience to produce various products and services and reorganize their business structures are fundamental requirements of agile systems. Companies have adopted agile methodologies to respond to rapid growth and continuous market changes [34]. Some essential agile methods in the supply chain domain include increasing the frequency of new product introductions [35], speeding up customer service delivery [36], developing centralized and collaborative planning [35], utilizing information technology to synchronize/integrate activities in production, design, and development [36], [37], the ability to change supplier lead times [36], reducing development cycle times [36], and increasing the frequency of new product introductions [35].

Higher levels of turbulence and volatility also characterize today's market. Consequently, supply chains are more vulnerable to disruptions, increasing the risk of business continuity [38]. While in the past, the primary goal in supply chain design was to minimize costs or optimize services, the focus today is on resilience [39]. Resilience is recognized as the supply chain's ability to cope with unforeseen disruptions [10]. The objectives of resilience strategies have a dual aspect [40]: 1) to return the disrupted system to a desired state within an acceptable time frame and cost, and 2) to reduce the impact of disruption threats by changing the level of effectiveness. The relationship between resilience and sustainability can be found in the supply chain literature [41].

Farbod et al. [42] researched the influence of supply chain dynamics on financial performance using a supply chain disruption structure approach. The findings of their study indicate that the dynamics and flexibility of the supply chain during disruptions affect financial performance, with supply chain resilience mediating. In their research, Sahoo et al. [43] focus on industry 4.0 within supply chain management. They emphasize the importance of future studies in developing standardized frameworks and best practices that enable businesses to effectively utilize the transformative capabilities of the digital era in their supply chains.

Furthermore, this study investigates the impact of digital transformation initiatives on supply chain management performance and how they contribute to strengthening the resilience of supply chains [43]. To achieve sustainability, this system must manage conditions that extend the probabilities of future events while capitalizing on current opportunities. It must ensure adaptability and changeability, and identifying factors to enhance system resilience might facilitate reaching sustainability. Representative examples of primary resilience methods in the supply chain literature include strategic stocks [39], reducing lead times [44], maintaining dedicated transportation fleets [45], flexible supply base/sourcing flexibility [39], sourcing strategies to enable supplier replacement [45], and creating a comprehensive view of the supply chain [46]. Flexible transportation [39], clear visibility into downstream inventories, and demand conditions [47].

The green management approach is recognized for reducing costs using more efficient resources such as water, energy, and raw materials [48]. Companies that do not effectively utilize resources risk losing potential business opportunities and incurring losses due to increased prices of scarce goods [49]. In their study, Song et al. [50] examined the pricing decisions of the dual-channel supply chain for low-carbon consumers. They highlight the notable rise in consumer consciousness regarding environmental preservation in a sustainable manner. Consequently, consumer behavior and perspectives have transformed. It necessitates manufacturers and suppliers to adapt their strategies to maintain competitiveness. Enterprises must thoroughly assess their pricing strategies for online and offline channels, ensuring both platforms' harmonious coexistence and consistent growth. Sahu and Goswami [51] explore the process of green supplier selection through a multicriteria decision-making approach. Their study highlights the significance of this aspect in sustainable supply chain management within the current corporate landscape. With the increasing focus on environmental issues and stricter regulations, organizations are realizing the necessity of integrating eco-friendly practices into their operations. Consequently, selecting suppliers who share these principles has become crucial.

Anaraki et al. [52] conducted a study on evaluating and selecting suppliers in the supply chain using the fuzzy analytical network process approach. Their research aimed to propose a novel method for assessing and rating suppliers. They identified various evaluation criteria and attributes and employed the Simple Multi-Attribute Rating Technique (SMART) method for selection. Malekinejad et al. [53] comprehensively examined a closed-loop supply chain to mitigate electronic waste. The primary goal of this research was to establish a holistic framework that promotes the reduction of electronic waste by implementing a sustainable closed-loop supply chain. The findings of this study indicate that rather than disposing of a substantial amount of electronic waste, emphasis should be placed on cost reduction through the enhancement of recycling processes. There exists a relationship between adopting green management practices and sustainability. Some authors emphasize companies' specific contributions to developing green products for prominent sustainability [54]. This expectation arises as a product is considered green when its environmental and social performance in production, use, and disposal significantly improves compared to regular or competitive products [55]. Some proposed green practices in the supply chain domain include environmental collaboration with suppliers [56], ISO 14001 certification [57], waste minimization [58], reverse logistics [57], environmental monitoring of suppliers [4], energy consumption reduction [59], material reuse/recycling and packaging [4], environmental collaboration with customers [60], and reverse logistics [49].

2.2 | Fuzzy Inference System

FS theory is introduced as a valuable tool for characterizing uncertainty and imprecision in data without the need for complex mathematical relationships. These models have a distinct advantage in that they can represent nonlinear functions in a more understandable language style rather than relying solely on numerical values. By using fuzzy rules, these models provide a convenient representation of human understanding in a readable manner. Fuzzy logic is particularly well-suited for evaluating social sustainability indicators, as it can effectively model complex systems with undefined dynamics and inputs. It can also process knowledge and data represented in various ways, including mathematical models, linguistic rules, numerical values, or linguistic statements [61].

Jin et al. [62] conducted a comprehensive review titled "advancing explainable artificial intelligence for disease diagnosis," discussing an FIS with interpretable fuzzy rules. This review aims to provide a fundamental understanding of interpretability and fuzzy rules. Using the FIS, Bozanic et al. [63] examined the complexities surrounding ranking challenges, risks, and threats in their study. In the field of security and defense, defining these factors is inherently intricate and uncertain. To tackle this issue, the researchers incorporated fuzzy logic into their model.

Charolina and Fitriyadi [64] applied the Mamdani fuzzy model to evaluate the satisfaction level of social welfare services at the "Professor Dr. Suharso" integrated center in Surakarta. Their study primarily concentrated on utilizing Mamdani's fuzzy model to assess the satisfaction level of social welfare services. By employing the FIS logic of Mamdani's model, the researchers examined the relationship between service and satisfaction levels. In their study, Tsang et al. [65] investigate the impact of Blockchain sharding on the performance analytics of e-commerce supply chains in the context of Industry 5.0. The researchers propose a customized evaluation framework that utilizes an FIS based on the green supply chain operations reference model.

Yusmiati et al. [66] conducted a research project to assess the sustainability performance of the sago industry supply chain. They utilized a multicriteria adaptive fuzzy inference model, the FIS, to evaluate sustainability across three economic, social, and environmental dimensions. The research conducted by Nezhadkian et al. [67] introduces a model for new product development in business companies. The study adopts a grounded theory approach and fuzzy method, employing a qualitative framework.

2.3 | Using Indicators as a Benchmarking Tool

Until recently, criteria were mainly used to compare commercial performance or the utilized product. The shift from executions to methods can be considered the concept's evolution [68]. Composite benchmarking refers to using analytical and comparative tools that contain accessible knowledge, easily understandable and usable even without specific managerial skills [69], [70]. Performance-oriented quantifiable criteria that perform a probable comparison with a target, highlighting any gap between the criterion and the investigated performance, are considered valid, according to Drew [71], only when used as a diagnostic tool in the initial stages of benchmarking, i.e., when this process is regarded as a tool for organizational improvement. The processes behind executions need to be analyzed to understand the improvements needed and how to make them. Additionally, creating a criterion for performance is challenging as it heavily depends on situational factors.

Benchmarking on methods differs as it compels a company to comprehend the approaches and actions presented by tools from the initial stage of planning and compares approaches used with established approaches. The tool can only be executed when this comprehension occurs. Additionally, defining gaps between current methods and goals highlights the need for activating improvements. It indicates how improvements can be made to enhance learning processes and catalyze change [72].

In literature, some indicators have been suggested as benchmarking tools. From a macro perspective, Haggins [73] proposes a unified index to assess the relative economic competitiveness of regions and locales in Britain, suggesting an analysis of local and regional criteria. Additionally, the World Bank [74] developed a logistics performance index as a benchmarking tool to assist countries in identifying opportunities in their commercial logistics performance. This index evaluates countries' international trade logistics performance (customs performance, infrastructure quality, and timeliness of shipments) and internal determinants for overall logistics performance (infrastructure, services, border and time procedures, and supply chain reliability).

Considering sustainability perspectives, Lau [75] recommends a composite index to benchmark green logistics performance among industries and countries. Ruano et al. [76] studied improving sustainability in Belize's ecotourism sector. The researchers used the Delphi technique and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to analyze key indicators of sustainable ecotourism. By incorporating FS theory, this integrated approach provided valuable insights into the environmental, social, cultural, economic, political, and intrinsic dimensions of ecotourism in Belize.

Sıcakyüz [77] conducted a bibliometric analysis to investigate the utilization of Data Envelopment Analysis (DEA) in Supply Chain Management. The research findings revealed significant potential for DEA to effectively evaluate future studies addressing Supply Chain Management sustainability issues. Farnam and Darehmiraki [78] examine the solution to the hesitant fuzzy linear programming problem to address hesitant fuzzy multi-objective problems. The study uses the hesitant fuzzy approach to model the multi-objective and three-level supply chain management problem. However, some indicators are developed based on the company's viewpoint. For instance, Tanana et al. [79] proposed a total quality index as a benchmarking tool to help managers evaluate a comprehensive quality management program in organizational processes. In the supply chain domain, Azodo et al. [79] suggested an index for assessing the greenness and resilience of a supply chain. In a parallel study, they created an index for assessing the agility and leanness of individual companies and their related supply chains [7].

Scoring methods vary because they compel a company to understand the tools' methods, processes, and actions from the first stage of comparing the approaches used with the established approaches. This understanding can only occur when this gap is understood. Furthermore, defining the gaps between current methods and goals highlights the need for activating improvements. It demonstrates how improvements can be made to enhance the learning process and work as an engine for change.

The criteria obtained from a comprehensive review of the literature and other published reports in the field of LARG were also confirmed by a focused group with experts in the field of the medical equipment supply chain [80]-[83]. The obtained LARG criteria of a supply chain are shown in *Table 1*.

Table 1. Extracted indicators from the theoretical background.

	The Main Criteria	Main Actions	Subcriteria
The LARG of the supply chain of hospital medical equipment	Lean	Operational	Reduction in the total cost of the supply chain [26], [80]
			Reduction in the total lead time of purchase orders [55], [80], [81], [83]
			JIT production or timely responsiveness [29], [55], [81]
		Management	Optimal inventory management [55], [80], [81]
			Comprehensive quality management [28], [80], [81], [83]
			Long-term relationships with suppliers [29], [55], [80], [81], [83]
			Customer relationship management [26], [55], [83]
	Agile	Operational	Utilization of information technology for activity coordination/integration [37], [55], [83], [84]
			Reduction in the lead time for supply chain development [44], [55],[84]
			Enhanced flexibility in production [33], [80], [81]
		Management	Alteration of delivery plans to meet customer needs [34], [83]
			Increased frequency of introducing new products [34], [55], [80]
			Speeding up service improvement for customers (timely product delivery to customers) [37], [55], [80]
			Introduction of significantly value-added products for customers [35], [83]
	Resilience	Operational	Commitment to procurement contracts (purchasing capacity, whether used or unused) [80], [83]
			Reduction in the rate of lost sales [80]
			Information sharing among supply chain members [80], [83]
		Management	Establishment of a supply chain risk management culture [80], [83]
			Creation of a flexible supply and sourcing base [39], [55]
			Flexible transportation management [39], [55]
			Clear and explicit downstream inventory vision and demand conditions [47], [55], [80], [81]
	Green	Operational	Reduction in material diversity used in product manufacturing [54], [85]
			Use of renewable resources [4]
			Reduction in fossil energy consumption [86]
		Management	Reuse or recycling of recyclable materials (waste management) [57], [58], [87]
			Implementation of reverse logistics [57], [87]
			Environmental monitoring/surveillance of suppliers [4]
			Collaboration with product designers and suppliers to mitigate and eliminate environmental product impacts [56]

3 | Methodology

In the present study, a questionnaire has gathered data from medical equipment supply chain experts. The sample area includes government hospitals in the Hamedan province.

3.1 | Fuzzy Inference System

The fundamental philosophy behind fuzzy theory is to establish a mathematical framework that accurately studies ambiguous and imprecise concepts in decision-making. Fuzzy theory enables a gradual transition from precise and quantifiable concepts to vague and imprecise ones, incorporating imprecise concepts into mathematical models and accurately representing them. By understanding fuzzy logic and its core principles, decision-makers can model and make informed decisions on complex issues and problems, even when faced with insufficient and uncertain data.

The FIS plays a crucial role in evaluating qualitative concepts like sustainability, as it enables the modeling and analysis of complex, uncertain, and imprecise systems. These systems are designed to handle fuzzy and ambiguous input data, making them suitable for various applications where precise mathematical models are not feasible. Additionally, they can integrate expert knowledge and human reasoning into computational systems, further enhancing their capabilities [62].

In this research, a "FIS" model, a mathematical technique using fuzzy logic, is employed to map a given input to an output. The fuzzy inference process consists of three vital components: 1) fuzzification, 2) if-then rules, and 3) defuzzification [88]. Considering the ambiguity in the data, a fuzzy inference approach could be suitable for resolving ambiguity and assessing the LARG of the hospital medical equipment supply chain [89]. Mamdani's most common fuzzy inference technique is known as the Mamdani model. Zadeh [90] introduced the fuzzy logic model in 1965.

3.2 | Functionality of FIS

The Mamdani FIS comprises four main stages: 1) variable fuzzification, 2) rule assessment, 3) rule aggregation, and 4) defuzzification. *Fig. 2* illustrates the primary structure of the Mamdani FIS.

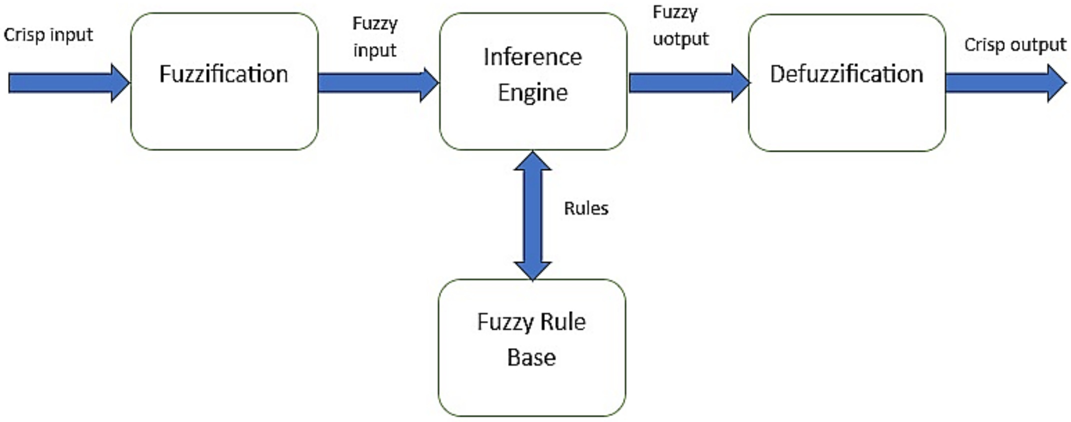

Fig. 2. Basic structure of a Mamdani FIS.

3.2.1 | Fuzzification

The first stage of the Mamdani FIS is fuzzification. In this stage, precise inputs are transformed into fuzzy inputs using various membership functions recognized as linguistic variables. A membership function is a graphical representation that reduces linguistic terms and demonstrates an FS graphically [91]. Common membership functions include triangular, Gaussian, trapezoidal, and bell curves. Thus, fuzzification aims to allocate numerical input values to degrees of membership in specified FSs. This research uses the Gaussian membership function due to its softness and non-zero value in all points and brevity. There are no rules for defining the membership function, and they are determined based on expert knowledge, data, and information extracted from previous assessments and available documentation.

$$gsn(x: a, \sigma) = \exp\left(\frac{-(x-a)^2}{\sigma^2}\right).$$

3.2.2 | Inference engine

The inference engine uses fuzzy rules in the knowledge base to generate fuzzy output. This output cannot be directly used in any process or system; thus, it must be converted into a clear output. A fuzzy rule is an expression that is defined in an if-then form. The fuzzy rule follows: If X is A, Y is B. In this fuzzy rule, X and Y are linguistic variables, and A and B are FSs. After defining all if-then rules, an aggregation process combines all rules to obtain a singular FS.

The process of implementing fuzzy inference for the set of rules Ru^l: IF x_1 is A_1^l and ... and x_n is A_n^l, Then y is B^l is as follows:

I. Determining the membership function for the fuzzy relation $A_1^l \times A_2^l \times ... \times A_n^l$ in $U = U_1 \times U_2 \times ... \times U_n$:

$$\mu_{A_1^l \times A_2^l \times ... \times A_n^l}(x_1, x_2, ... x_n) = \mu_{A_1^l}(x_1) * \mu_{A_2^l}(x_2) * ... * \mu_{A_n^l}(x_n),$$

which in this system (*) is t-norm.

II. Determining the membership function of the rule based on the requirement of minimum Mamdani

$$\mu_{B'}(y) = \max_{l=1:m}\left[\sup_{x\in U}\min\left(\mu_{A'}(x), \mu_{A_1^l}(x), \dots, \mu_{A_n^l}(x), \mu_{B^l}(x)\right)\right].$$

III. Determining the membership function of the fuzzy relation related to the combination M of the rule by the Mamdani community method

$$Q_M = \bigcup_{i=1}^{m} Ru^l \quad s.t: \quad \mu_{QM}(x,y) = \mu_{R^1}(x,y) \dotplus \dots \dotplus \mu_{R^M}(x,y),$$

where $\dotplus$ is S-norm.

IV. Inference using Mamdani combination and arbitrary FS A' in U

$$\mu_{B'}(y) = \sup_{x\in U}\left[\mu_{B'}(x,y), \mu_{QM}(x,y)\right].$$

Fuzzy rules

In this stage, specialized knowledge is formulated in the form of rules, including the rules that should be used in decision-making. These rules are generally based on personal experience and intuition. There are different types of fuzzy rules, the most common of which are called connection rules and are used in Mamdani FISs. A rule consists of two main parts: 1) an antecedent block (between if and then) and 2) a posterior block (following the then), if (anterior) then (posterior) [92].

Two essential features of fuzzy rules are their continuity and compatibility, which are [93]:

I. A set of fuzzy if-then rules is continuous if adjacent fuzzy rules share their predecessor. Intuitively, the continuity of the set of rules means the smoothness of the system's behavior.

II. A set of fuzzy if-then rules is compatible if it does not contain rules with the same antecedent and different followers. In other words, the set of rules does not have contradictions. Although the premises and subsequent components in the above discussion have single arguments, a law can be written with multiple arguments.

3.2.3 | Defuzzification

Defuzzification is a vital part of an expert system. Fuzzification is the final stage in the "FIS" process [94]. This process converts fuzzy input into clear output. Defuzzification is classified into several types, including the Mean of Maximum (MOM), Center of Area (COA), Largest of Maximum (LOM), Bisector of Area (BOA), and Smallest of Maximum (SOM). The COA defuzzification method, also known as the Center of Gravity (CoG), is the most common method used in fuzzification [95]. In the CoA fuzzification method, the fuzzy controller first calculates the scaled area under the membership functions within the output variable range. Then, the fuzzy logic controller uses the equation below to calculate the geometric center of this area, where CoA is the center of the area, X represents the linguistic variable value, and X_min and X_max denote the linguistic variable range [96].

$$COA = \frac{\int_{X_{min}}^{X_{max}} f(x) * x}{\int_{X_{min}}^{X_{max}} f(x)}.$$

3.3 | Developing a Fuzzy Inference Model for Assessing the LARG of Hospital Medical Equipment Supply Chain

The current research aims to create a hierarchical fuzzy model to assess the LARG of the hospital medical equipment supply chain. This model has been implemented to predict the LARG of the hospital medical equipment supply chain using MATLAB software. *Fig. 3* displays the structure of a hierarchical fuzzy inference model for assessing the LARG of the hospital medical equipment supply chain. The fuzzy model development method for assessing the LARG of the hospital medical equipment supply chain includes several stages.

An FIS is a powerful decision-making tool that calculates the LARG of a hospital's medical equipment supply chain with a numerical value that is easier to understand. This numerical value can help decision-makers easily understand the LARG situation of the hospital's medical equipment supply chain and take necessary measures if necessary. The FIS can provide an effective solution for complex systems, and the method can be easily modified to improve performance. The results of this research are a FIS method to deal with real-world problems, including ambiguity and uncertainty, especially the LARG nature of the hospital medical equipment supply chain, to overcome uncertainty and obtain a clear, appropriate output. The FIS method can be used for LARG evaluation of different types of supply chains. An FIS helps us understand and evaluate the effect of each input parameter on the LARG degree of the hospital medical equipment supply chain, which can help decision-makers. Since Mamdani's "FIS" is rule-based, it is easier to understand. The FIS can apply different types of fuzzification methods, and it is also possible to apply various types of membership functions.

The proposed model includes two intermediate fuzzy stages and a final fuzzy stage. The first fuzzy stage consists of seven input parameters divided into two main operational and managerial actions, forming 27 fuzzy rules for each main criterion's managerial actions and 81 fuzzy rules for each main criterion's operational actions. Finally, this stage contains 432 fuzzy rules. The second fuzzy stage consists of two input parameters to evaluate each main criterion, 25 fuzzy rules for each main criterion, and finally, this stage has 100 fuzzy rules. The third fuzzy stage consists of four input parameters to evaluate LARG; 625 fuzzy rules are defined for this criterion. This model is developed to investigate the LARG of a hospital's medical equipment supply chain with a dataset considering 28 essential parameters. The research results show that the above 28 parameters affect the LARG of the hospital's medical equipment supply chain.

In the first stage, sub-criteria for the four main criteria are categorized into management and operational activities. The fuzzy model structure in this stage demonstrates that for each main criterion, there are three sub-criteria for operational activities and four for management activities. Qualitative measures are defined as very low, low, moderate, high, and very high in the first stage of the assessment using inference systems. The output of this stage is divided into five categories: 1) very low, 2) low, 3) moderate, 4) high and 5) very high.

The second stage comprises a fuzzy model structure for each criterion with operational and management inputs. In the assessment of using inference systems in the second stage, the categories include very low, low, moderate, high, and very high, which are utilized from the output of the first stage fuzzy model. The output of this stage is divided into five categories: 1) very low, 2) low, 3) moderate, 4) high and 5) very high.

In the third and final stage, the structure of the fuzzy model uses the outputs of the second stage for evaluating the LARG of the hospital medical equipment supply chain. In the assessment of using inference systems in the third stage, the categories are very, very low, very low, low, moderate, high, very high, and very very high.

After determining the range for each parameter, the next step is to select the membership function for each input and output. 'FS theory' is used to fuzzify the inputs and outputs, thereby transforming the FS into a precise number. The membership function is a curve that specifies how each point in the input space is assigned a membership value. *Fig. 4* and *Fig. 5* present membership functions for some input and output variables.

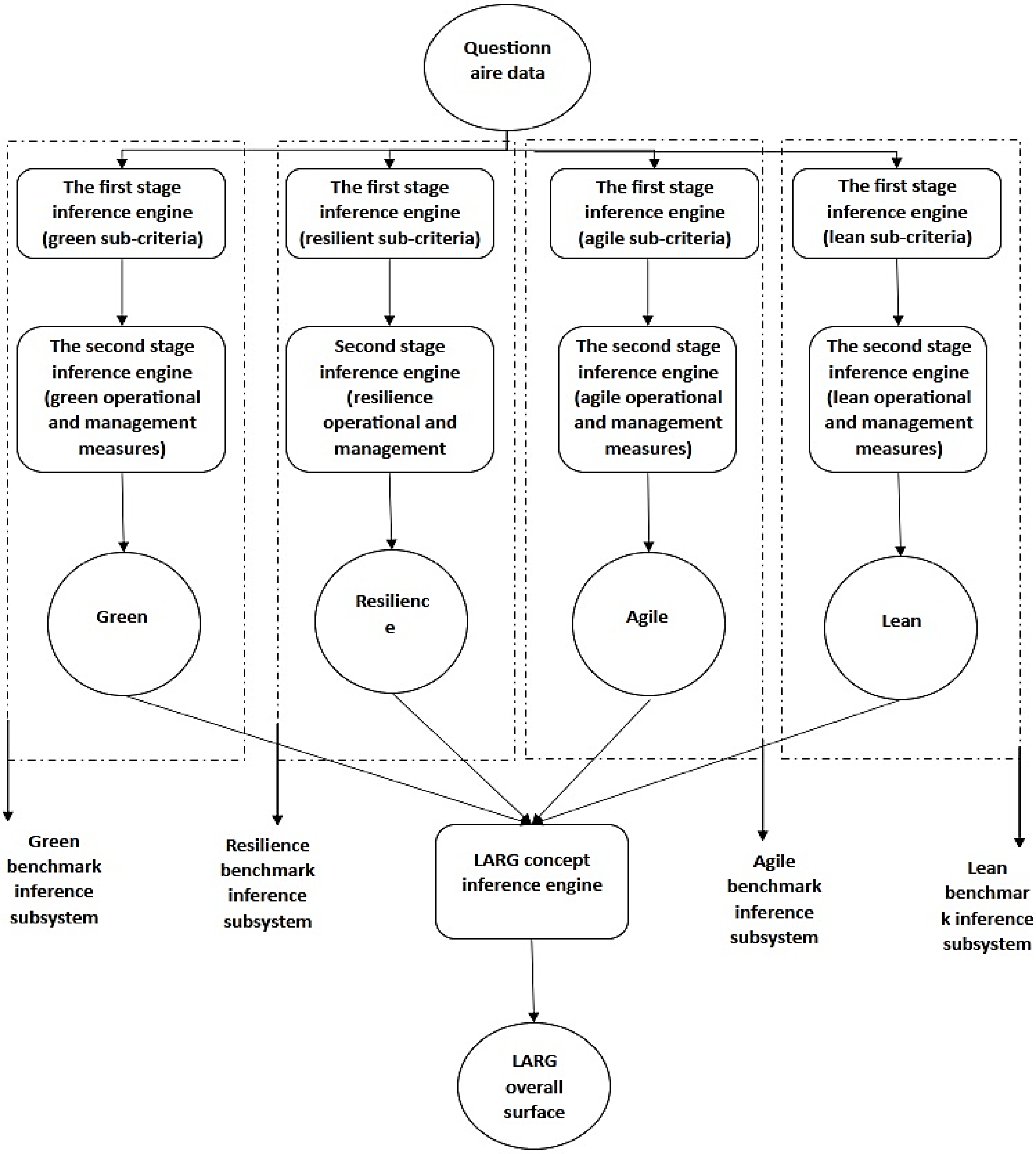

Fig. 3. Overview of the inference system.

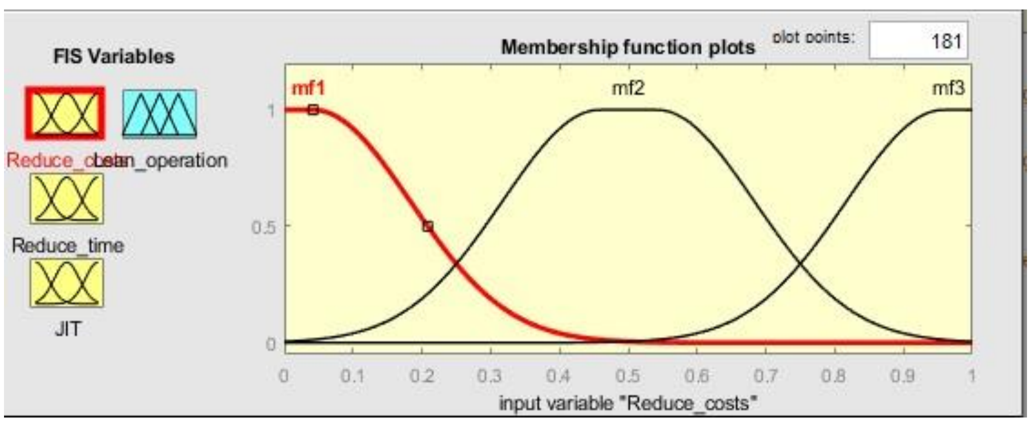

Fig. 4. Membership function for the first-stage input variable of reducing supply chain costs.

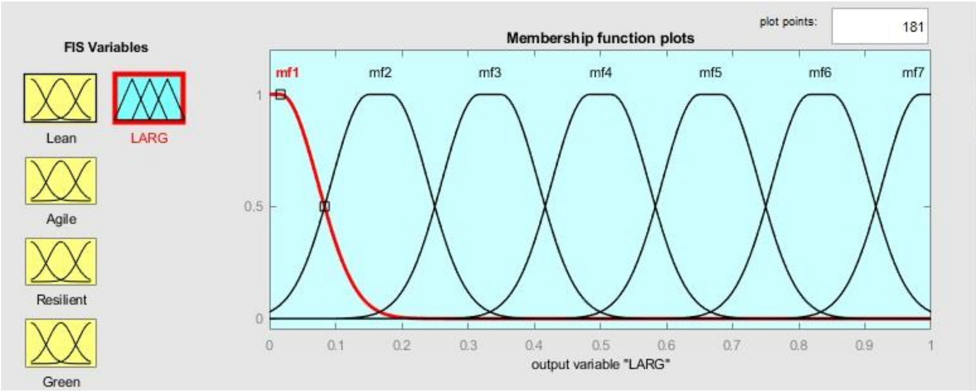

Fig. 5. Membership function for the output variable of the third stage.

The next step involves writing linguistic rules. The basis of these rules is a set of linguistic statements in the form of if-then rules that include antecedents and consequents related to the 'AND' operator. *Fig. 6* provides if-then rules for various stage models. After defining all if-then rules, all fuzzy rules are evaluated in the inference engine and then gathered to obtain a unified rule. Finally, the fuzzy reasoning method converts the fuzzy output into a clear output.

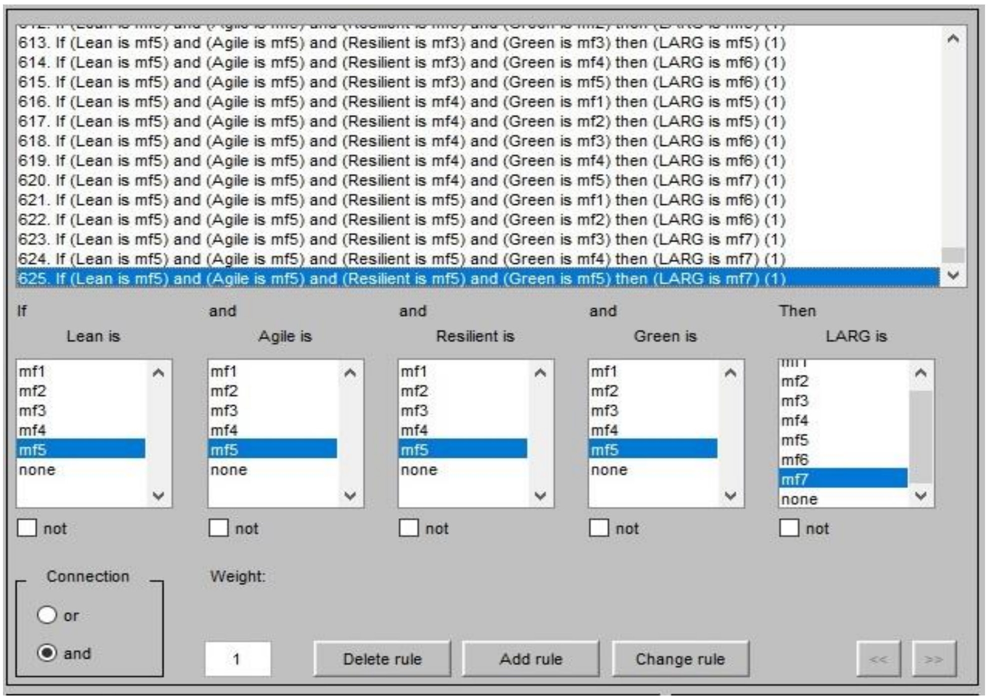

Fig. 6. Fuzzy rules for the final stage of the fuzzy model.

4 | Results

4.1 | Fuzzy Inference Engine Models for the First Stage

Fig. 7 shows evaluation rules for lean operational actions with three input parameters: total supply chain cost reduction, purchase order cycle time, and timely production. The rule-based representation in *Fig. 7* indicates that the model's value of lean operational actions equals 0.671, obtained respectively as 0.9, 0.85, and 0.65 through centroid defuzzification for reducing total supply chain costs, total purchase order cycle time, and timely production.

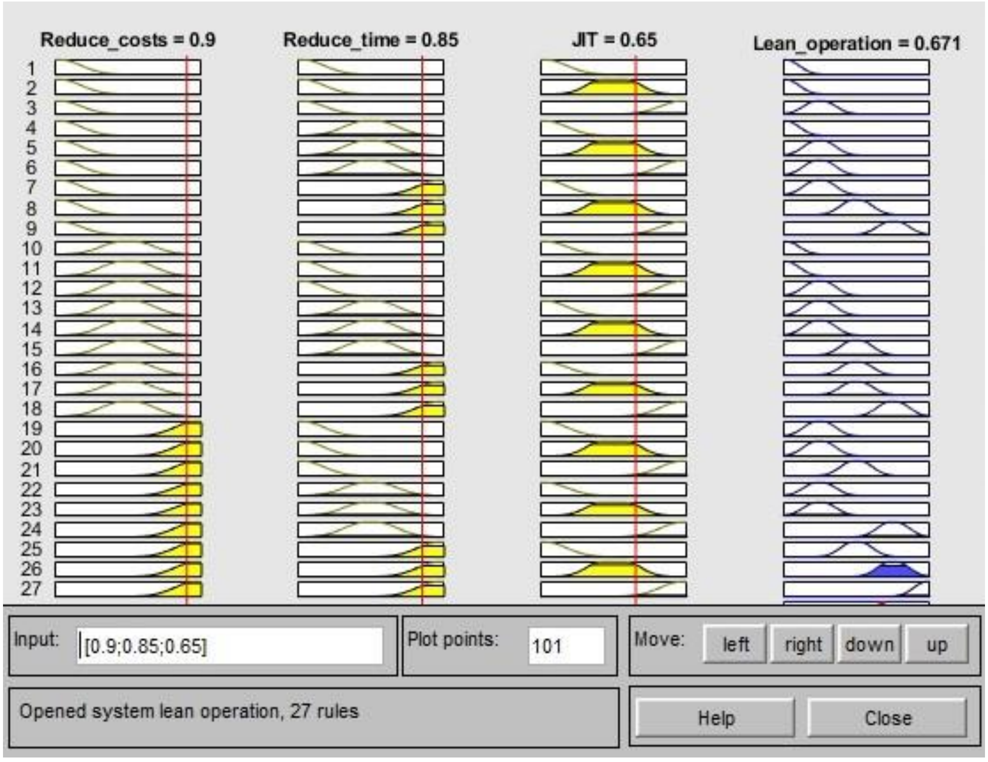

Fig. 7. Fuzzy model rules for lean operational actions.

Fig. 8 illustrates the effects of reducing total supply chain costs and total purchase order cycle time on Lean operational actions. This figure demonstrates that the higher the importance of reducing total supply chain costs and total purchase order cycle time, the higher the value of lean operational actions. *Fig. 8* also shows that decreasing the importance of reducing total supply chain costs and total purchase order cycle time leads to a decrease in the value of lean operational actions and vice versa. *Fig. 8* represents lean operational actions to reduce supply chain costs and purchase order cycle time as inputs. In contrast, the third input (timely production) remains hidden in this view.

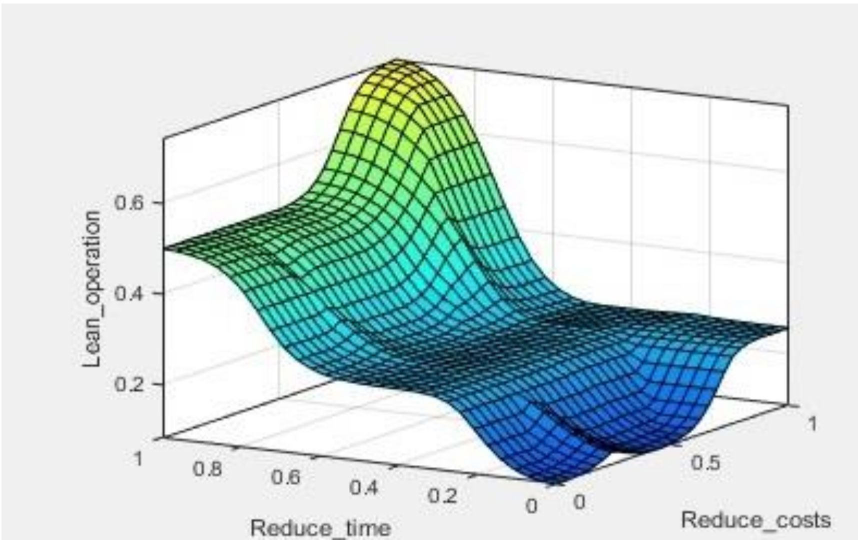

Fig. 8. Surface plot of the fuzzy model for lean operational actions.

Fig. 9 displays evaluation rules for lean management actions with four input parameters: optimal inventory management, comprehensive quality management, long-term relationships with suppliers, and customer relationship management. The rule-based representation in *Fig. 9* indicates that the value of lean management actions in the model equals 0.689, obtained respectively as 0.9, 0.85, 0.76, and 0.7 through centroid defuzzification for optimal inventory management, comprehensive quality management, long-term relationships with suppliers, and customer relationship management.

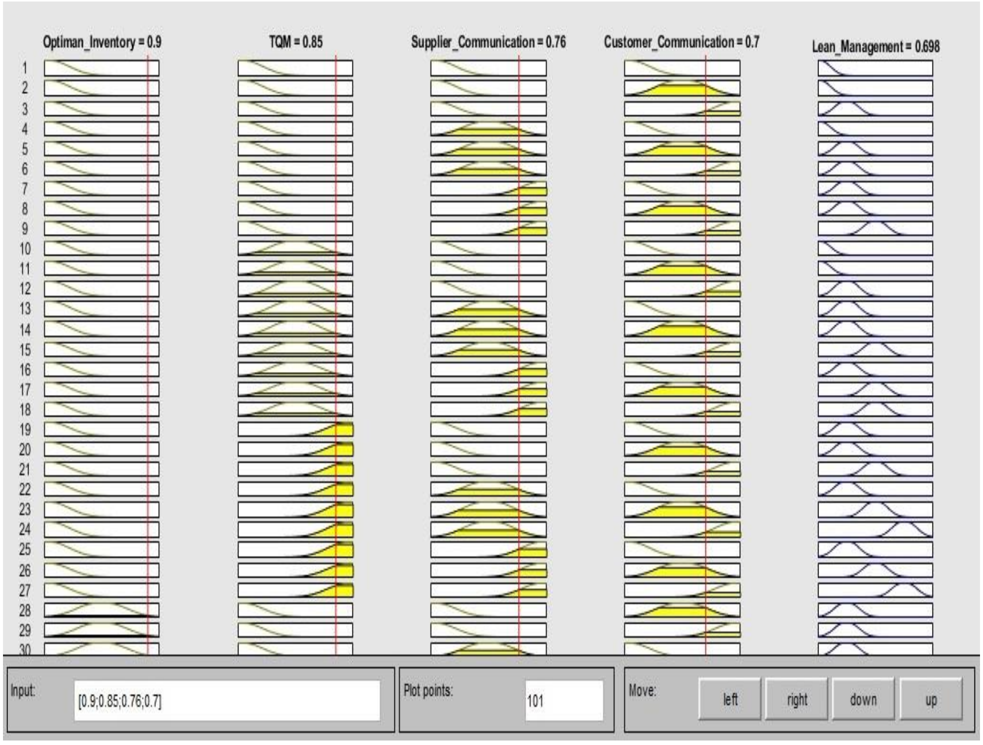

Fig. 9. Fuzzy model rules for lean management actions.

Fig. 10 shows the effects of optimal inventory management and total quality management on lean management measures. This figure shows that the greater the importance of optimal inventory management and comprehensive quality management, the higher the value of lean management measures. *Fig. 10* also indicates that as the importance of reducing the total cost of the optimal inventory management chain and total quality management decreases, the value of lean management measures decreases and vice versa. *Fig. 10* shows lean management actions as a function of optimal inventory management and total quality management as inputs. In contrast, the other two inputs (long-term supplier relationships and customer relationship management) are hidden in this view.

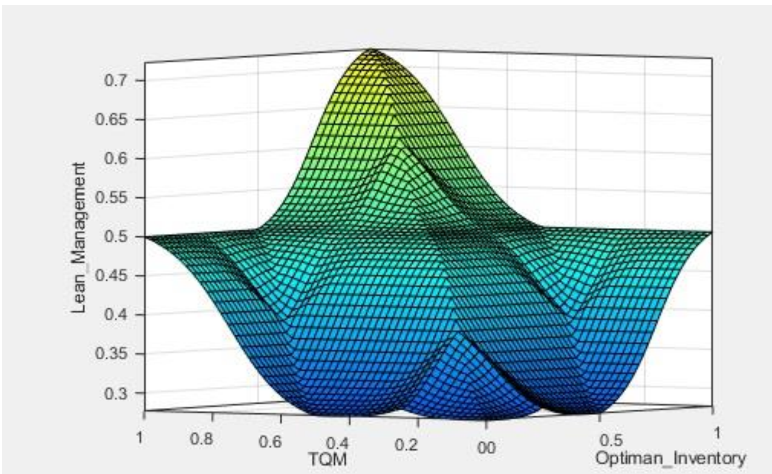

Fig. 10. Surface plot of the fuzzy model for lean management actions.

Fig. 11 depicts evaluation rules for Agile operational actions with three input parameters: using information technology for activity coordination/integration, reducing supply chain development cycle time, and improving production flexibility. The rule-based representation in *Fig. 11* shows that the value of Agile operational actions in the model is equal to 0.646, obtained respectively as 0.75, 0.9, and 0.7 through centroid defuzzification for using information technology for activity coordination/integration, reducing supply chain development cycle time, and improving production flexibility.

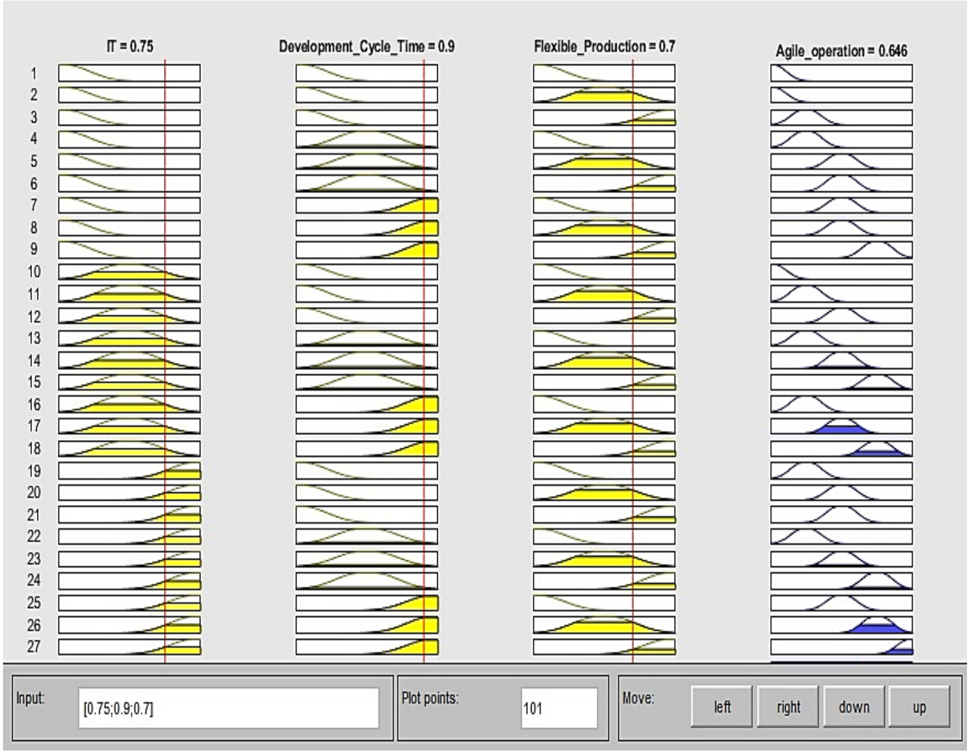

Fig. 11. Fuzzy model rules for Agile operational actions.

Fig. 12 illustrates the effects of using information technology for activity coordination/integration and reducing supply chain development cycle time on Agile operational actions. This figure demonstrates that the higher the significance of using information technology for activity coordination/integration and reducing supply chain development cycle time, the higher the value of Agile operational actions. *Fig. 12* also shows that decreasing the importance of using information technology for activity coordination/integration and reducing supply chain development cycle time leads to a decrease in the value of Agile operational actions and vice versa. *Fig. 12* represents Agile operational actions as a function of using information technology for activity coordination/integration and reducing supply chain development cycle time as inputs, while the other input (improving production flexibility) remains hidden in this view.

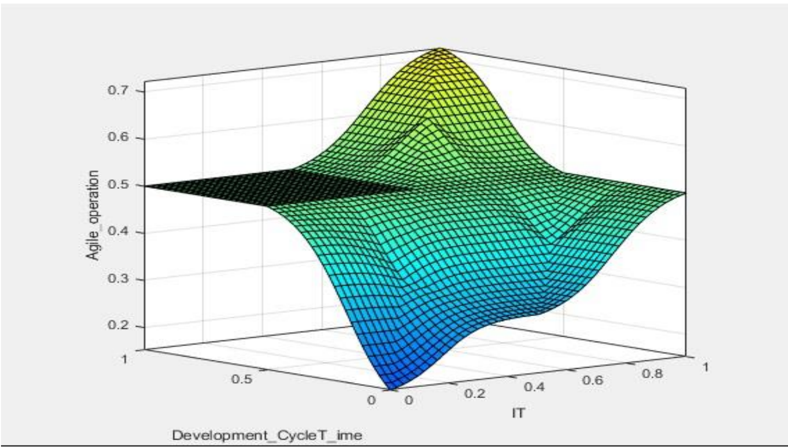

Fig. 12. Surface plot of the fuzzy model for Agile operational actions.

Fig. 13 displays evaluation rules for Agile management actions with four input parameters: 1) changing delivery plans to respond to customer needs, 2) increasing the frequency of introducing new products, 3) speeding up customer service improvement (timely product delivery to customers) and 4) introducing significantly value-added products for customers. The rule-based representation in *Fig. 13* indicates that the value of Agile management actions in the model equals 0.687, obtained respectively as 0.7, 0.9, 0.8, and 0.75 through centroid defuzzification for changing delivery plans to respond to customer needs, increasing the frequency of introducing new products, speeding up customer service improvement (timely product delivery to customers), and introducing significantly value-added products for customers.

Fig. 13. Fuzzy model rules for Agile management actions.

Fig. 14 illustrates the effects of changing delivery plans to respond to customer needs and increasing the frequency of introducing new products on Agile management actions. This figure demonstrates that the higher the significance of changing delivery plans to respond to customer needs and increasing the frequency of introducing new products, the higher the value of Agile management actions. *Fig. 14* also shows that decreasing the importance of changing delivery plans to respond to customer needs and increasing the frequency of introducing new products leads to a decrease in the value of Agile management actions and vice versa. *Fig. 14* represents Agile management actions as a function of changing delivery plans to respond to customer needs and increasing the frequency of introducing new products as inputs. In contrast, the other two inputs (speeding up customer service improvement and introducing significantly value-added products for customers) remain hidden in this view.

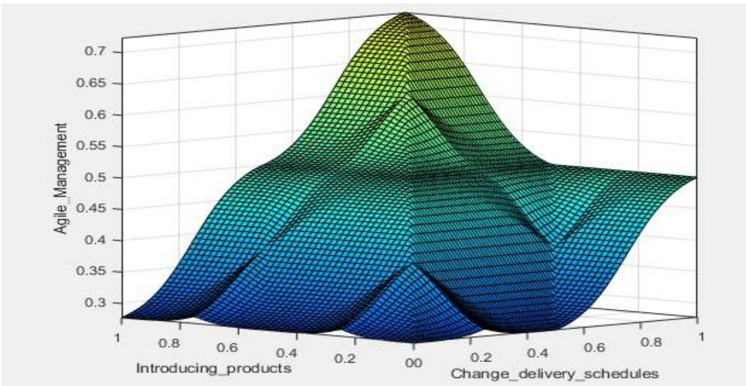

Fig. 14. Surface plot of the fuzzy model for Agile management actions.

Fig. 15 shows evaluation rules for resilience operational actions with three input parameters: commitment to material supply contracts (purchase capacity whether used or unused), reduced lost sales ratio, and sharing information among supply chain members. The rule-based representation in *Fig. 15* indicates that the value of resilience operational actions in the model equals 0.672, obtained respectively as 0.6, 0.9, and 0.8 through centroid defuzzification for commitment to material supply contracts (purchase capacity whether used or unused), reducing the ratio of lost sales, and sharing information among supply chain members.

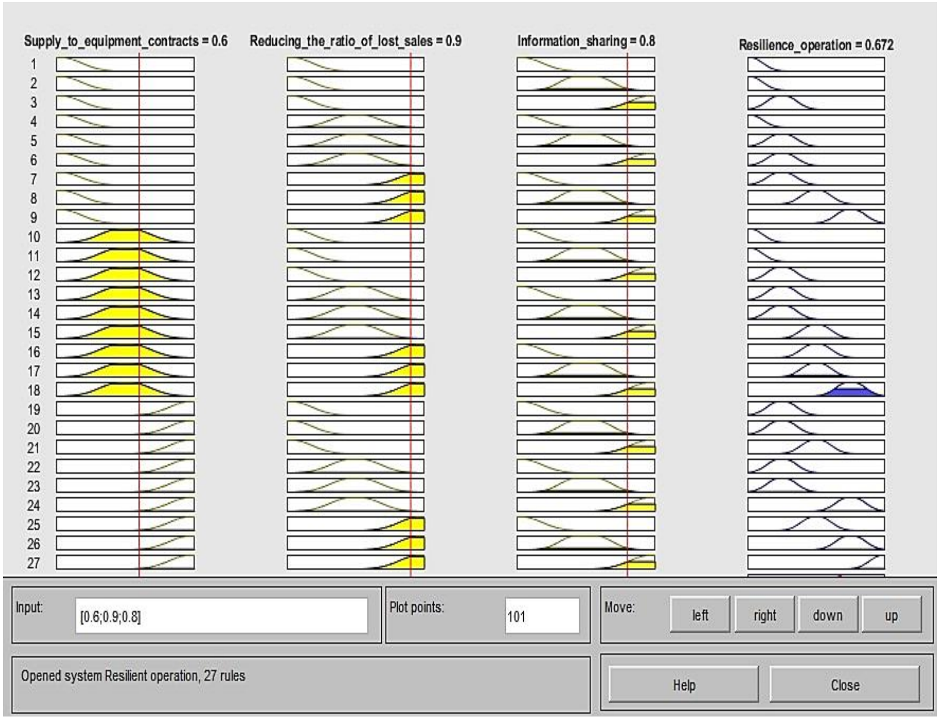

Fig. 15. Fuzzy model rules for resilience operational actions.

Fig. 16 demonstrates the effects of commitment to supply contracts and reducing the ratio of lost sales on resilience operational actions, indicating the resilience metric. This figure illustrates that with a higher commitment to supply contracts and a greater reduction in lost sales ratios, the value of resilience operational actions concerning resilience metrics increases. Furthermore, *Fig. 16* shows that by diminishing the significance of commitment to supply contracts and reducing lost sales ratios, the value of resilience operational actions related to resilience metrics decreases, and vice versa. It depicts resilience operational actions concerning resilience metrics as a function of commitment to supply contracts and reduced lost sales ratios as inputs. In contrast, another input (sharing information among supply chain members) remains hidden in this depiction.

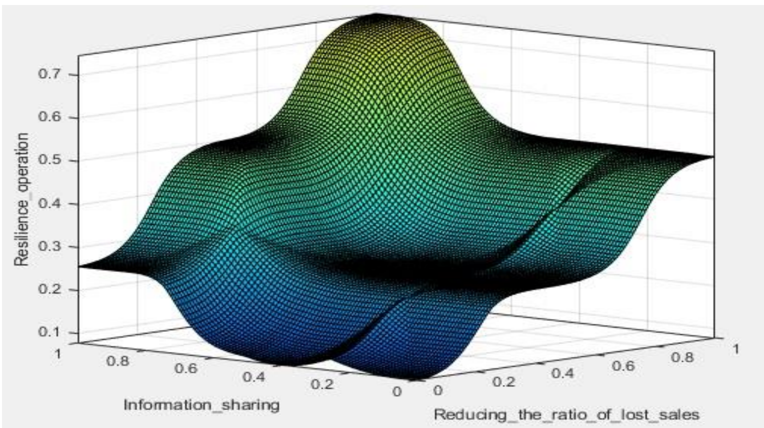

Fig. 16. Surface plot of the fuzzy model for resilience operational actions.

Fig. 17 illustrates the evaluation rules for management actions related to resilience metrics with four input parameters: 1) creating a risk management culture in the supply chain, 2) establishing flexible supply bases and sourcing, 3) flexible transportation management and 4) developing a clear view of downstream inventory and demand conditions. The rule-based representation in *Fig. 17* demonstrates that the value of management actions regarding the resilience metric in the model equals 0.728, obtained through the centroid defuzzification method for creating a risk management culture in the supply chain, establishing flexible supply bases and sourcing, flexible transportation management, and developing a clear view of downstream inventory and demand conditions, respectively, with values of 0.65, 0.9, 0.85, and 0.8.

Fig. 17. Fuzzy model rules for resilience management actions.

Fig. 18 depicts the effects of creating a risk management culture in the supply chain, establishing flexible supply bases, and sourcing on resilience management actions. This figure shows that the higher the importance of creating a risk management culture in the supply chain and establishing flexible supply bases and sourcing, the higher the value of resilience management actions. *Fig. 18* also indicates reducing the significance of creating a risk management culture in the supply chain and establishing flexible supply bases. Sourcing diminishes the value of resilience management actions, and vice versa. It displays resilience management actions as a function of creating a risk management culture in the supply chain, establishing flexible supply bases, and sourcing as inputs. In contrast, two other inputs (flexible transportation management and developing a clear view of downstream inventory and demand conditions) remain concealed in this illustration.

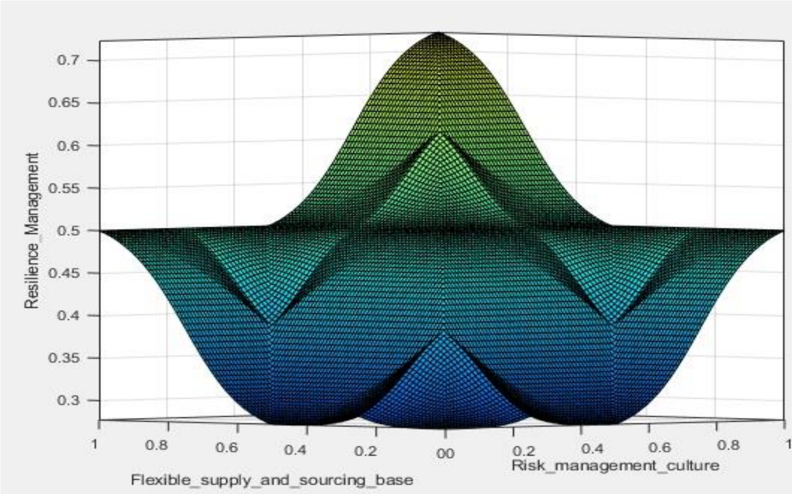

Fig. 18. Surface plot of the fuzzy model for resilience management actions.

Fig. 19 illustrates the evaluation rules for operational actions concerning the green metric with three input parameters: reducing material diversity used in product manufacturing, utilizing renewable resources, and reducing the consumption of fossil fuels. The rule-based representation in *Fig. 19* indicates that the value of operational actions concerning the green metric in the model equals 0.672, obtained through the centroid defuzzification method for reducing material diversity used in product manufacturing, utilizing renewable resources, and reducing the consumption of fossil fuels, with respective values of 0.8, 0.8, and 0.95.

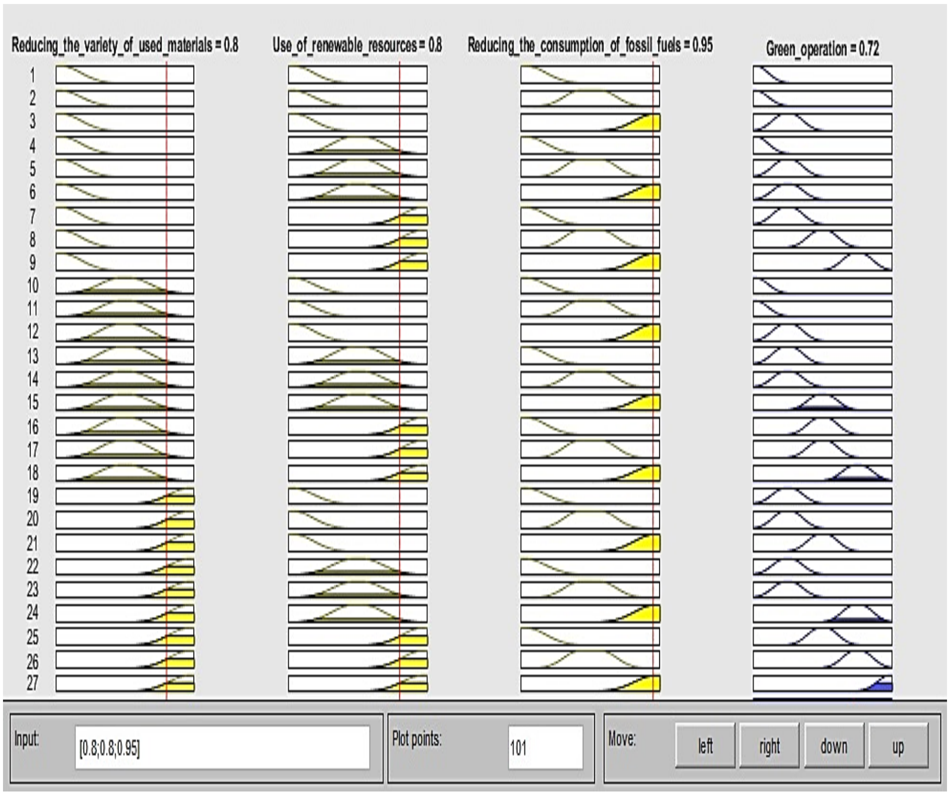

Fig. 19. Fuzzy model rules for green operational actions.

Fig. 20 displays the effects of reducing material diversity in product manufacturing and utilizing renewable resources on operational actions concerning the green metric. This figure demonstrates that with a greater reduction in material diversity used in product manufacturing and higher utilization of renewable resources, the value of operational actions concerning the green metric increases. *Fig. 20* also shows that by reducing the importance of reducing material diversity used in product manufacturing and utilizing renewable resources, the value of operational actions concerning the green metric decreases, and vice versa. It illustrates operational actions concerning the green metric to reduce material diversity in product manufacturing and utilize renewable resources as inputs. In contrast, another input (reducing the consumption of fossil fuels) remains hidden in this depiction.

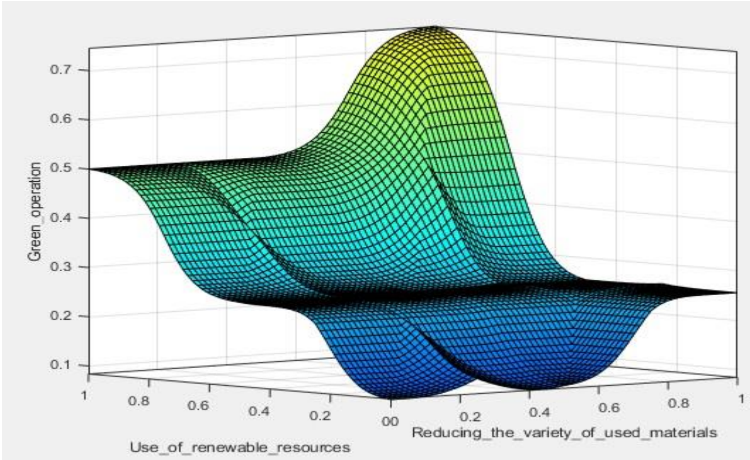

Fig. 20. Surface plot of the fuzzy model for green operational actions.

Fig. 21 shows the evaluation rules for green management actions with four input parameters: 1) reuse or recycling of recyclable materials (waste management), 2) reverse logistics management, 3) environmental monitoring of suppliers and 4) collaboration with product designers and suppliers to reduce and eliminate the environmental impacts of the product. The rule-based display in *Fig. 21* indicates that the value of green management actions in the model equals 0.728, obtained through the centroid defuzzification method, for reuse or recycling of recyclable materials (waste management), reverse logistics management, environmental monitoring on suppliers, and collaboration with product designers and suppliers, with values of 0.8, 0.7, 0.6, and 0.8 respectively.

Fig. 21. Fuzzy model rules for green management actions.

Fig. 22 demonstrates the effects of waste management and environmental monitoring on suppliers' green management actions. This figure illustrates that the higher the importance of waste management and environmental monitoring on suppliers, the higher the value of green management actions. *Fig. 22* also shows that reducing the significance of waste management and environmental monitoring on suppliers decreases the value of green management actions and vice versa. *Fig. 22* displays green management actions as a function of waste management and environmental monitoring of suppliers as inputs. In contrast, the other two inputs (reverse logistics management and collaboration with product designers and suppliers) remain hidden in this view.

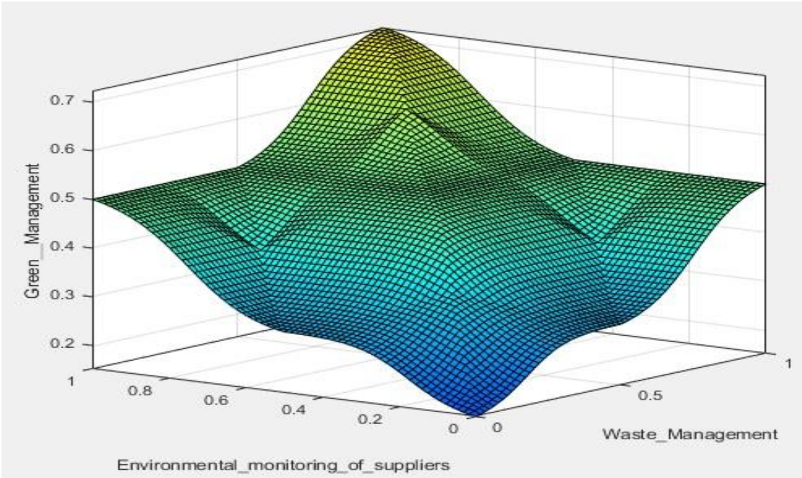

Fig. 22. Surface plot of the fuzzy model for green management actions.

4.2 | Fuzzy Inference Engine Models for the Second Stage

Fig. 23 displays the rule presenter for evaluating lean with two input parameters: 1) operational and 2) managerial. The rule-based display in *Fig. 23* demonstrates that the final lean value is 0.708 for the respective average values of operational lean and managerial lean, which are 0.671 and 0.698, using the centroid defuzzification method. This indicates that lean is significantly high using the centroid defuzzification method.

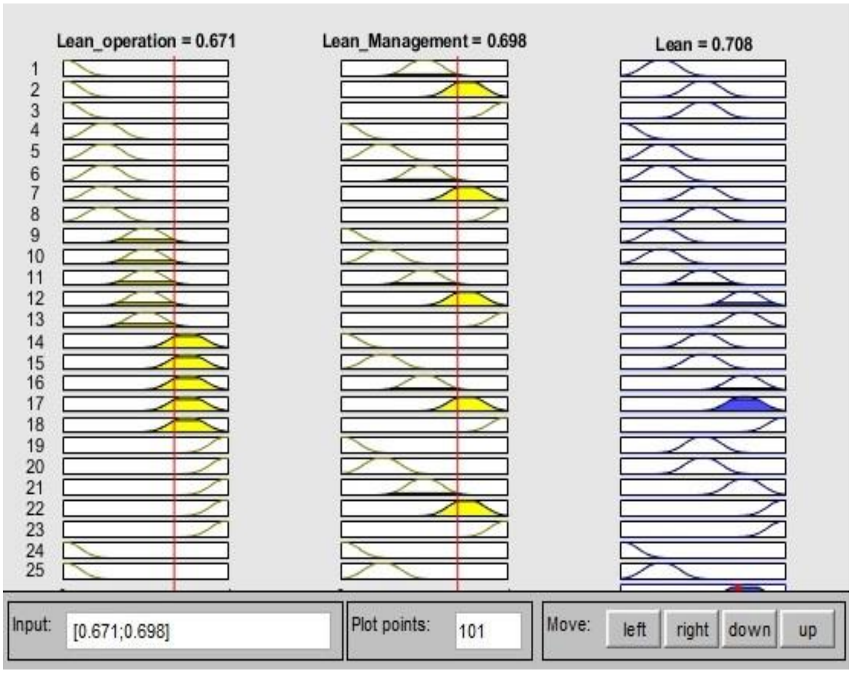

Fig. 23. Fuzzy model rules for lean.

Fig. 24 illustrates the effects of operational and managerial lean values on the final lean value. It indicates that the higher the operational and managerial lean values, the higher the final lean value. Increasing operational and managerial lean values increases lean value, and vice versa.

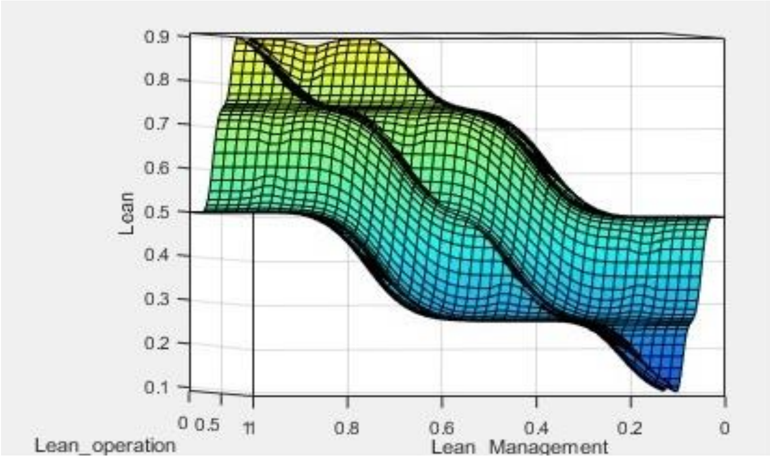

Fig. 24. Surface plot of the fuzzy model for lean.

Fig. 25 displays the rule presenter for agility assessment with two input parameters: 1) operational and 2) managerial agility. The rule-based display in *Fig. 25* shows that the final agility value is 0.693 for the respective average operational and managerial agility values, which are 0.646 and 0.687 using the centroid defuzzification method. This suggests that agility is significantly high using the centroid defuzzification method.

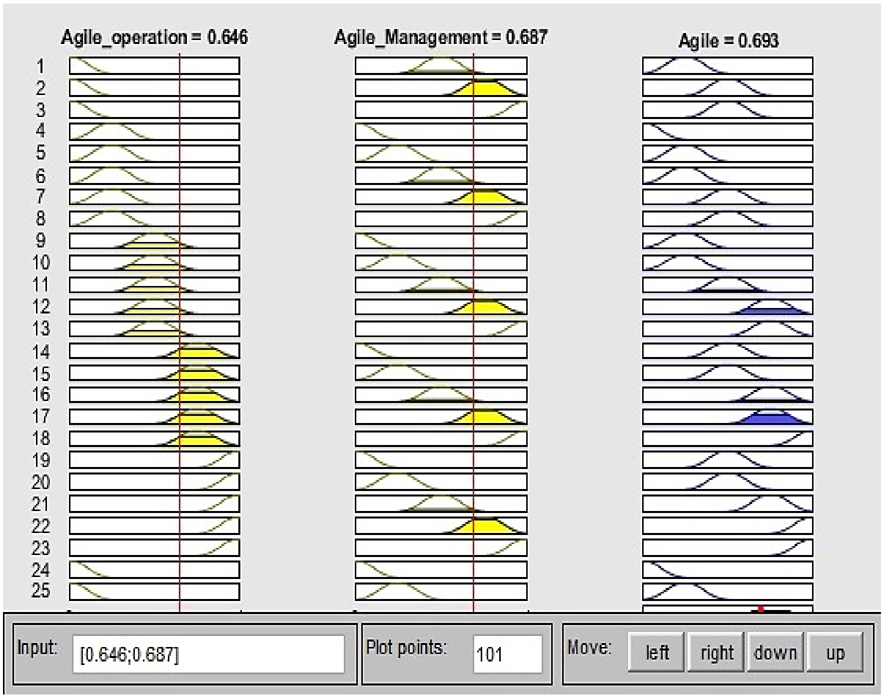

Fig. 25. Fuzzy model rules for Agile.

Fig. 26 demonstrates the effects of operational agility and managerial agility values on the final agility value. It shows that the higher the operational and managerial agility values, the higher the final agility value. Increasing operational and managerial agility leads to an increased agility value and vice versa.

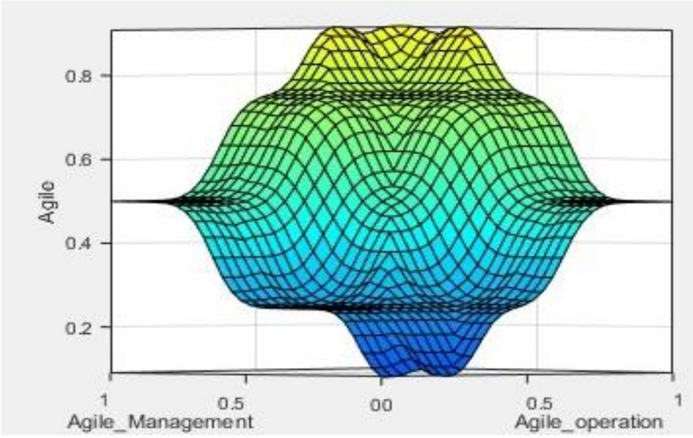

Fig. 26. Surface plot of the fuzzy model for Agile.

Fig. 27 displays the rule presenter for resilience assessment with two input parameters: 1) operational and 2) managerial resilience. The rule-based display in *Fig. 27* shows that the final resilience value is 0.728 for the respective average operational and managerial resilience values, which are 0.672 and 0.728 using the centroid defuzzification method. This indicates that resilience is significantly high using the centroid defuzzification method.

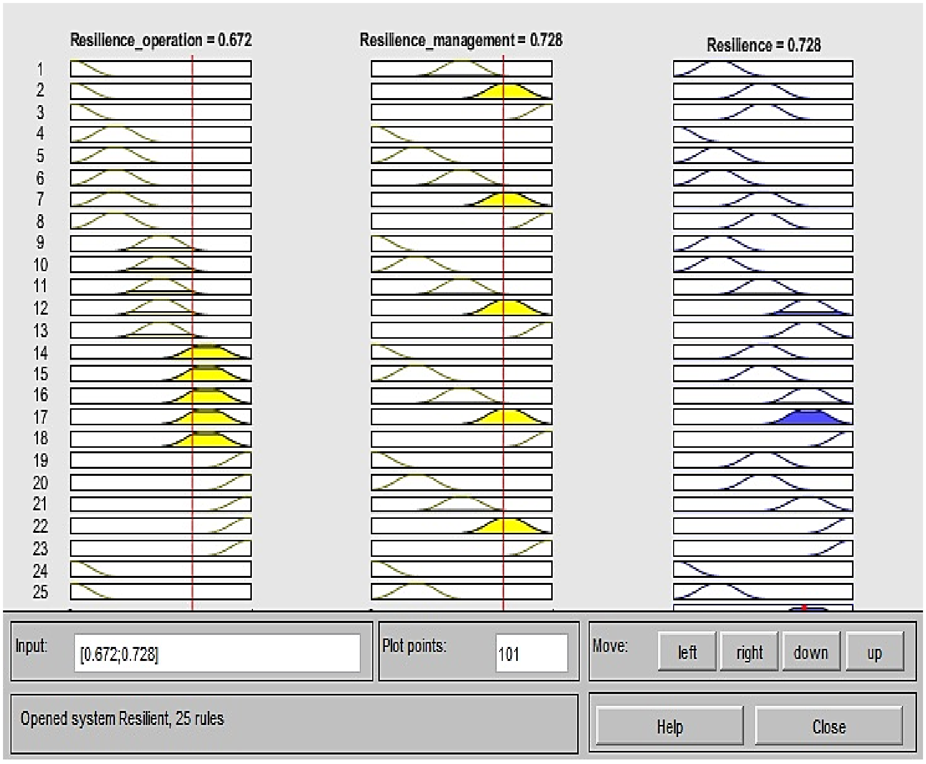

Fig. 27. Fuzzy model rules for resilience.

Fig. 28 illustrates the effects of operational resilience and managerial resilience values on the final resilience value. It demonstrates that the higher the operational and managerial resilience values, the higher the final resilience value. Increasing operational and managerial resilience values results in an increased resilience value, and vice versa.

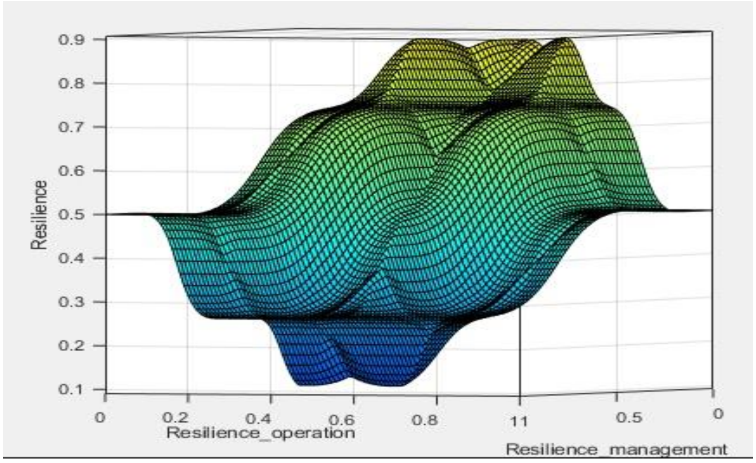

Fig. 28. Surface plot of the fuzzy model for resilience.

Fig. 29 displays the rule presenter for green assessment with two input parameters: 1) operational greenness and 2) managerial greenness. The rule-based display in *Fig. 29* shows that the final greenness value is 0.722 for the respective average values of operational greenness and managerial greenness, which are 0.72 and 0.661 using the centroid defuzzification method. This indicates that greenness is significantly high using the centroid defuzzification method.

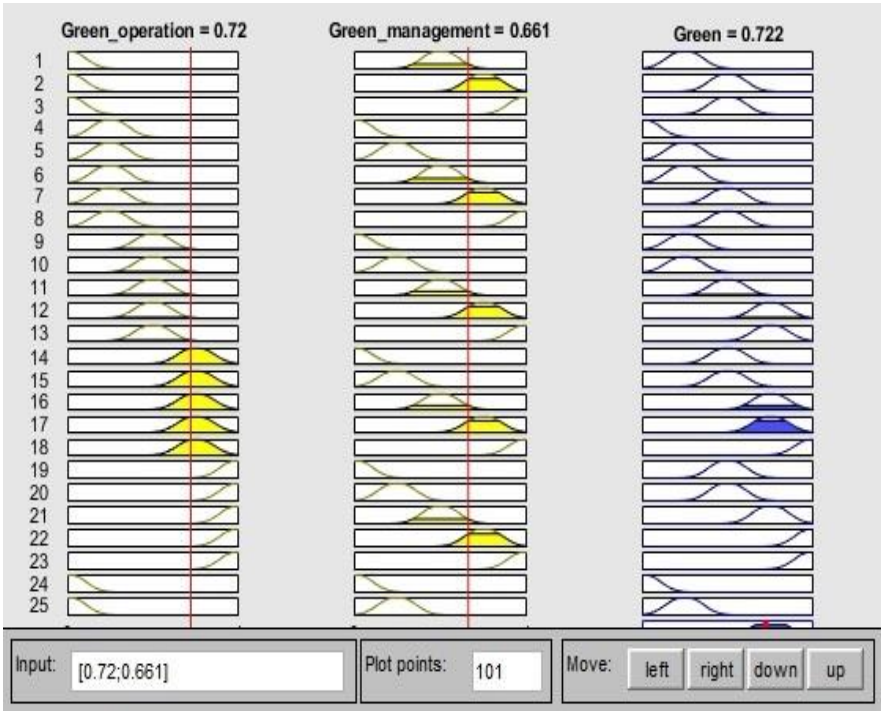

Fig. 29. Fuzzy model rules for green.

Fig. 30 demonstrates the effects of operational and managerial greenness values on the final greenness value. It shows that the higher the operational and managerial greenness values, the higher the final greenness value. Increasing operational and managerial greenness values leads to an increased greenness value, and vice versa.

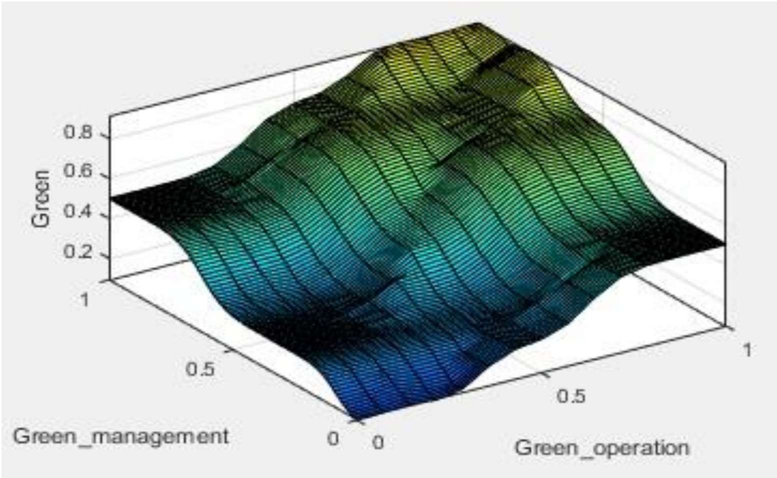

Fig. 30. Surface plot of the fuzzy model for green.

4.3 | Fuzzy Inference Engine Models for the Final Stage

Fig. 31 presents the rule presenter for evaluating the LARG of the medical equipment supply chain with four input parameters: 1) lean, 2) agility, 3) resilience and 4) greenness of the chain. The rule-based display in *Fig. 31* indicates that the final LARG value for the respective average values of lean, agility, resilience, and greenness is 0.787, which are 0.708, 0.696, 0.728, and 0.722 using the centroid defuzzification method. This demonstrates that the LARG of the supply chain is significantly high using the centroid defuzzification method.

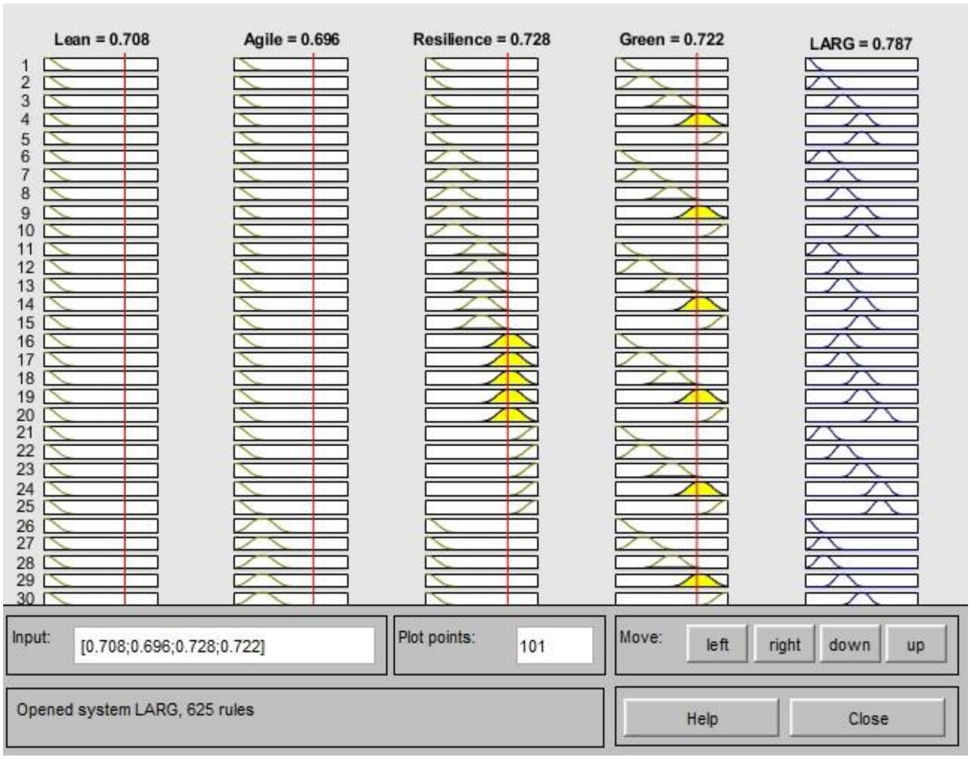

Fig. 31. Fuzzy model rules for LARG.

Fig. 32 to *Fig. 37* show the effects of lean, agility, resilience, and greenness values on the final LARG value of the supply chain.

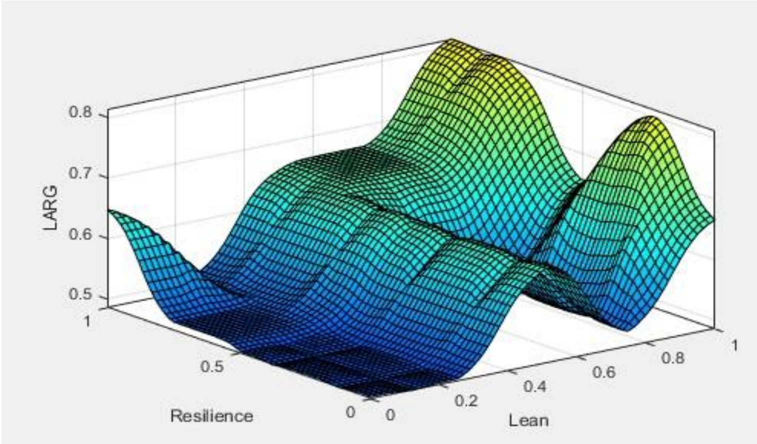

Fig. 32. Effects of lean and resilience values on the final LARG value.

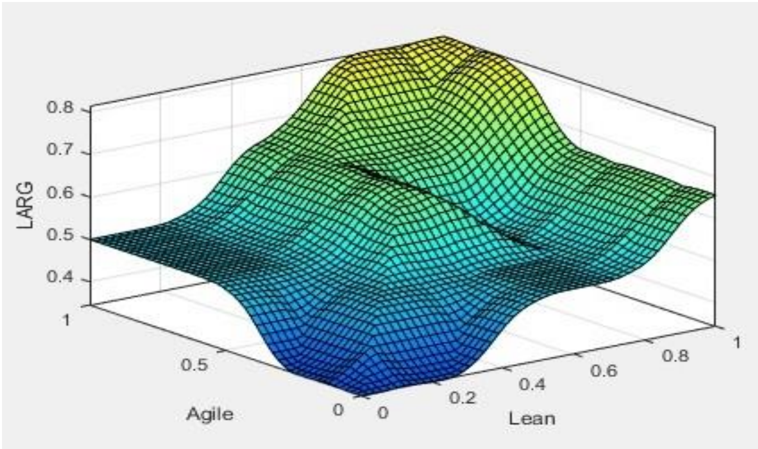

Fig. 33. Lean and agility values affect the final LARG value.

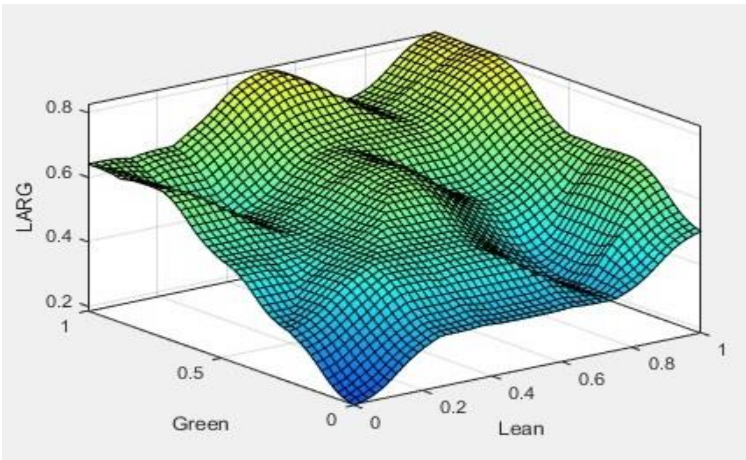

Fig. 34. Effects of lean and greenness values on the final LARG value.

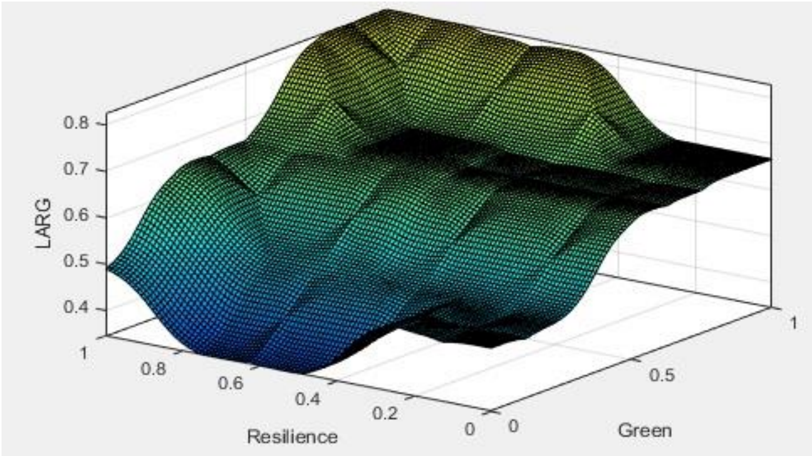

Fig. 35. Effects of resilience and greenness values on the final LARG value.

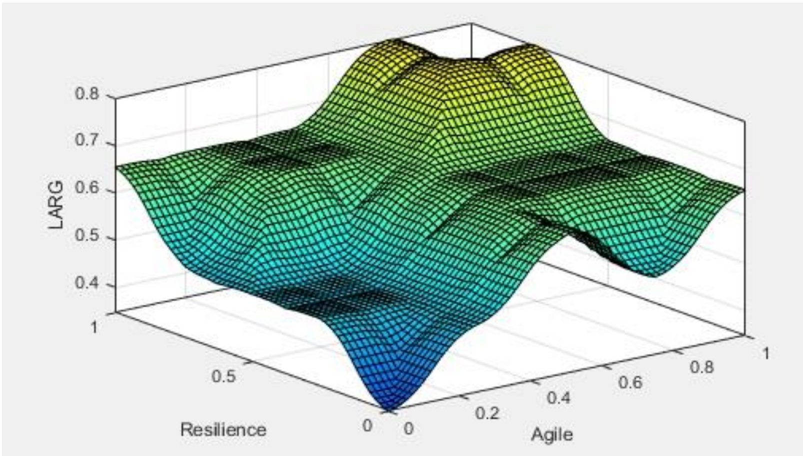

Fig. 36. Effects of agility and resilience values on the final LARG value.

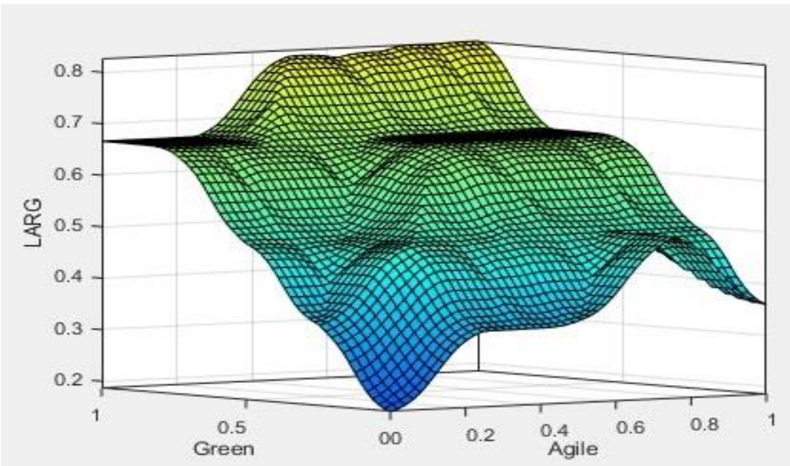

Fig. 37. Effects of agility and greenness values on the final LARG value.

5 | Discussion

This study employed the 'FIS' approach to construct an inference engine to evaluate the LARG of the Madani Hospital's medical equipment supply chain. MATLAB's fuzzy logic was the computational tool for modeling the overall system. The 'min' was used as the implication method, the 'max' for the aggregation method, and the centroid defuzzification method was utilized for fuzzification. The results of this research on assessing the LARG of the medical equipment supply chain using the 'FIS' approach demonstrate that the final measurement of the LARG of the medical equipment supply chain is a function of each of the 28 sub-criteria inputs. The measurement of the LARG of the medical equipment supply chain indicates the overall LARG based on the four main criteria of lean, agility, resilience, and greenness. Three FSs for the input indices were considered, including 'high,' 'medium', and 'low.' Output values were divided into seven classes. In general, seven FSs, which are 'very, very high,' 'very high,' 'high,' 'medium,' 'low,' 'very low,' and 'very, very low,' were considered for this study in evaluating the LARG value of the medical equipment supply chain.

Few studies have used various artificial intelligence approaches to measure the LARG of the medical equipment supply chain. The strength of the 'FIS' method compared to other artificial intelligence methods lies in its simplicity and ability to deal with uncertainty and evaluate the main criteria and values of various sub-criteria in defining the concept of LARG in the medical equipment supply chain. This makes the model unified for this examination. The FIS is an inference process addressing uncertainty and ambiguity.

The system proposed by this study offers several advantages when compared to the supply chain performance evaluation models found in the literature:

I. Contrary to the LARG assessment of supply chain models that integrate mathematical programming approaches or multicriteria decision methods, FIS models permit the modeling of nonlinear causal connections between input and output metrics. Additionally, it facilitates adaptation to the usage environment by leveraging historical data.

II. Unlike the previous models, the proposed system utilizes a wide range of metrics associated with various attributes of LARG, such as Information Technology, Long-term relationships with suppliers, responsiveness, cost, and information sharing.

III. The advantage of using models based on fuzzy logic and other techniques that rely on crisp numbers is their capability to model imprecise values and uncertain variables through the fuzzy representation of input variables. The FIS aims to replicate human reasoning by establishing cause-and-effect relationships between variables while considering uncertain scenarios. Consequently, the system calculates the output value by considering the combination of all scenarios represented by the activated rules and their corresponding degrees of activation.

IV. One advantage is that determining the performance values of the output variables using FIS models is more transparent and straightforward. This is because it enables the identification of the decision rules that support the obtained results. Consequently, the enhanced interpretability of the information provided by these decision rules can instill greater confidence in operations managers when making decisions to enhance the performance of the supply chain.

6 | Conclusion

Developing a robust medical equipment supply chain encompassing the four pillars of LARG is widely acknowledged as a formidable challenge for many companies. Successfully achieving the distinct objectives of each pillar simultaneously serves as evidence of this claim. Consequently, enhancing the LARG capabilities of a supply chain provides a significant advantage for companies. However, managing a LARG supply chain effectively requires accurate measurement of its magnitude. It is essential to recognize that the inherent vagueness in investigating the LARG aspects of a supply chain further complicates this problem.

Additionally, evaluating the LARG performance of a supply chain involves considering multiple criteria, resulting in a substantial amount of subjective or ambiguous data. Therefore, developing an effective model is crucial for improving the evaluation process and addressing these shortcomings. To this end, an integrated approach based on service and manufacturing criteria was proposed to evaluate LARG in supply chains. This study employs the 'FIS' Mamdani, using the non-fuzzy centroid defuzzification method. This approach was validated through a real case study. Proper interpretation of the obtained results can provide valuable insights and practical applications for supply chain managers and researchers. The result shows that when the level of leanness is 0.708, agility is 0.696, resilience is 0.728, and greenness is 0.722, the LARG value of the final supply chain (0.787) is very high.

Future studies can focus on using an adaptive neural-FIS method that combines a neural network with a FIS. Also, for future research, more input parameters can be added by developing this model, and other membership functions can be used to create a more accurate and complete model. Experts can monitor the criteria using the fuzzy Delphi method and then use it in the model.

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Author Contribution

The first author (Ramin Pabarja): this author had the primary role in idea generation, research design, data collection, formal analysis, and article writing. He has also participated in providing supplementary cases as one of the main authors. The second author (Gholamreza Jamali): this author was involved in research design, data verification, formal analysis, review, and project planning. He has also participated in writing the article and providing supplementary material as one of the co-authors. The third author (Khodakaram Salimifard) contributed to the data collection and formal analysis for the research. He has also participated in writing the article and reviewing the supplementary cases as one of the co-authors. Fourth author (Ahmad Ghorbanpur): this author was involved in data verification, review, and project planning. He has also participated in writing the article and reviewing the supplementary cases as one of the co-authors. All authors have read and approved the manuscript. Only individuals who contributed significantly to the reported work are credited as authors.

Data Availability

The questionnaire used in this research to collect data from hospital medical equipment supply chain experts is available at the following link: (https://survey.porsline.ir/s/yTwjXfFU).

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