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# A Comprehensive Evaluation Model for Sustainable Supply Chain Capabilities in the Energy Sector

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**Abstract:** This study introduces a comprehensive model to evaluate multiple capabilities within the sustainable supply chain evaluation framework. The primary aim is to determine the significance of various capabilities in the context of sustainable supply chains. The research involved a sample of sixteen companies operating in Iran's energy sector. The findings indicate that the majority of these companies are at level two in terms of capability. Therefore, it is recommended that these companies employ this model to assess their capability levels and identify any existing gaps. Methodologically, a checklist tool was used to refine the criteria using the fuzzy Delphi method. Subsequently, an appropriate model was chosen and developed by reviewing existing evaluation models. The criteria were compared and finalized using the Analytic Hierarchy Process. Finally, the criteria were further refined and validated through a fuzzy expert system, incorporating Adaptive Neuro-Fuzzy Inference System and Fuzzy Inference System. The developed model was then simulated and validated using MATLAB Simulink software (R2017b).

**Keywords:** sustainable supply chain; capability evaluation; fuzzy expert system; simulation; energy

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## 1. Introduction

The supply chain functions as a intricate amalgamation of processes designed to fulfill customer needs, spanning various tiers of the network—from suppliers and manufacturers to transportation, warehousing, retailers, and end-users. Its primary objective is to enhance customer satisfaction while minimizing costs. The overarching aim across these chains, from suppliers to consumers, is to deliver high-quality services and maximize productivity [1].

This research endeavors to establish a comprehensive model for evaluating multiple capabilities within a sustainable supply chain. It employs a combined quantitative and qualitative approach, thoroughly integrated into the research framework. Previous studies have underscored the identification of essential dimensions and criteria within the hierarchical structure of supply chains. Sustainability management involves strategic business initiatives aimed at mitigating environmental, economic, and social risks while enhancing corporate value, including stock valuation [2].

Further research is encouraged to explore diverse dimensions of sustainable supply chains, fostering collaboration among companies and enhancing operational efficiency [3]. In today's competitive landscape, the focus has shifted from inter-company competition to competition between supply chains. Supply chain management encompasses responsibilities ranging from raw material procurement to production, distribution, customer service, and post-sales support, necessitating the optimal management of these processes. Every supply chain endeavors to enhance its performance to meet customer expectations, necessitating suitable tools and metrics for measuring supply chain performance and effectiveness.

When exploring sustainable supply chain capabilities, it is essential to recognize the broader geopolitical and economic challenges affecting energy transitions, particularly in the Middle East and North Africa (MENA). Schuetze et al. (2023) highlight that countries like Jordan face unique barriers due to existing geopolitical interdependencies and domestic political factors [4]. While the expansion of renewable energy presents an opportunity for improved energy security and economic growth, these efforts are often hindered by technical constraints, a renewed reliance on fossil fuels, and centralized control over energy systems. This underscores the importance of adopting a comprehensive approach that considers not only operational efficiency and competitiveness, but also the political and economic forces shaping energy transitions. The sustainable supply chain assessment framework presented in this study is designed to address these complexities and provide a tool to help organizations manage both internal performance metrics and external influences. By incorporating these considerations, companies can better position themselves to achieve long-term sustainability and resilience, especially in regions facing challenges similar to those observed in Jordan. The success of any supply chain or business hinges on an effective performance measurement system, ensuring the timely measurement of critical parameters [5].

Fundamental to employing multivariate analysis methods are the dimensions of variables. Given the varied performance and activities within supply chains, the question arises as to which dimensions should be monitored or measured and how resulting outcomes should be analyzed [6]. Evaluating sustainable performance significantly impacts future competitive advantages in the industry [7]. Social dimensions are pivotal in supply chains, enabling product and procurement managers to devise robust strategies that address supply chain-related issues by emphasizing these dimensions. Implementing social sustainability at supplier sites can enhance buyer supply chain performance [8].

Establishing an effective performance measurement system is deemed essential to transitioning towards sustainable supply chain systems and economies within a greener world [9]. Sustainable supply chain management integrates corporate social responsibility objectives with green supply chain management, assisting organizations in achieving economic, environmental, and social goals, thereby enhancing overall organizational reputation among clients. Empirical research in sustainable supply chain management remains insufficient to comprehensively cover all dimensions. Historically, supply chain management has predominantly focused on economic objectives, with insufficient attention given to environmental and social goals. Modern supply chains must align with social and environmental responsibilities inherent in sustainable supply chains, thereby advancing the economic, environmental, and social dimensions of sustainability across the entire supply chain [10].

The implementation of a green supply chain necessitates a comprehensive evaluation of its performance across various dimensions. This evaluation is facilitated through the application of multi-criteria decision-making techniques. Additionally, addressing complex and ambiguous challenges within this context requires the adoption of fuzzy decision-making methodologies [11]. Experts and consultants argue that leveraging diverse datasets can confer a competitive edge to supply chains [12].

This study begins with an exploration of the research background, identifying core competencies and gathering insights from industry specialists within the energy sector. Subsequently, expert opinions are analyzed using the fuzzy Delphi group decision-making approach to ascertain key variables for designing a multifaceted expert system for sustainable supply chain capabilities.

The research methodology outlined in this study establishes a framework and proposes a model to effectively evaluate multiple capabilities within sustainable supply chains. It aims to address pertinent questions regarding performance evaluation, particularly within the energy industry context.

## 2. Literature Review

The evaluation of sustainable supply chain capabilities has been a growing area of interest due to the increasing emphasis on sustainability in business operations. The literature reveals a diverse range of approaches, from statistical tests to sophisticated mathematical models, primarily focusing on a limited number of variables. This study aims to address this gap by proposing a comprehensive evaluation model for assessing multiple capabilities within sustainable supply chains, particularly in the context of Iran's energy sector.

**The Role of the European Green Deal in Countries Outside the EU in the Energy Field:**

The European Green Deal is a comprehensive policy plan that was introduced by the European Commission in 2019 with the goal of making Europe the first climate-neutral continent in history by the year 2050. Despite being focused on the European Union (EU), this wide agenda affects other regions as well, especially those that are close by, like the Southern Mediterranean. Serena Sandri et al. investigated the possible effects of the Green Deal on the nations in this region in their 2023 study. Their research sheds light on the potential and hazards these nations confront as they try to match the EU's strict environmental standards with their energy strategies. Despite obstacles like scarce financial resources and technological advancements, Sandri and her co-authors point out that the Southern Mediterranean countries have an opportunity to use the Green Deal to progress their transitions to sustainable energy and fortify their economic linkages to the EU [13].

A number of other academics have looked into the European Green Deal's wider implications on non-EU nations in addition to [13], particularly in the energy sector. Namany et al., for instance, have examined the possibility of EU-MENA cooperation in renewable energy, highlighting the mutual advantages in accomplishing climate goals [14]. El-Katiri has similarly concentrated on the function of natural gas in the Middle East and North Africa's energy transition, elucidating the ways in which the European Green Deal might impact the energy markets and policies of the region [15]. Collectively, these studies add to the increasing corpus of research that emphasizes how energy transitions are interconnected on a global scale and how cooperation is essential to achieving sustainable development objectives.

**Connection to Theoretical Foundation:**

The studies reviewed provide a comprehensive understanding of sustainable supply chain capabilities, particularly in the context of the European Green Deal. Each study contributes to our theoretical foundation in the following ways:

Framework for Sustainable Practices: Research by authors such as [13] elucidates how the European Green Deal creates a framework for sustainable practices within supply chains. This framework emphasizes the integration of environmental, social, and economic dimensions, which align closely with our research objectives.

Challenges and Opportunities: Studies examining the implications of the Green Deal for non-EU countries highlight both challenges and opportunities in implementing sustainable practices. For instance, the work of [15] explores how geopolitical factors influence energy transitions in the MENA region, which informs our understanding of the complexities faced by Iranian companies in adapting to sustainable supply chain models.

The Interconnectedness of Supply Chain Dimensions: The literature illustrates that the successful implementation of sustainable supply chain capabilities requires a holistic approach that considers technological, operational, and organizational factors. Our model integrates these dimensions, building upon the findings of prior research that emphasizes their interconnectedness in achieving sustainability goals.

Guiding Policy Implications: The insights gained from the reviewed studies underscore the need for robust policy frameworks to support the transition toward sustainable supply chains. By incorporating these theoretical perspectives, our research aims to provide actionable recommendations that align with the objectives set forth by the European Green Deal.

**Energy Transformation in the MENA Region and Its Challenges:**

Scholars like Martin Keulertz and Benjamin Schuetze have extensively researched the intricate process of the energy transition in the MENA area. The region has a great deal of promise for the development of renewable energy due to its abundant solar and wind resources. However, a number of obstacles prevent this transformation from happening quickly and effectively. Keulertz's study emphasizes how crucial the water–energy–food (WEF) nexus is to comprehending the region's constraints, especially with regard to water shortages and how it affects energy-related initiatives [16]. Conversely, Schuetze's research explores the social and political dimensions of energy transitions, emphasizing how socio-political resistance and governance concerns frequently impede the uptake of renewable energy [17].

The shift is further complicated by the complexity of the region's supply chain. Large-scale renewable energy project implementation and maintenance are made more difficult by a lack of infrastructure and technology transfer, as well as the geopolitical unrest that permeates most of the MENA region. The region's dependence on fossil fuels, which is bolstered by subsidies and strong economic interests, makes the transition to greener energy choices even more difficult. According to Schuetze's analysis of the sociopolitical environment, strong elite interests frequently impede the implementation of critical reforms and impede the shift to sustainable energy.

In order to enable a successful energy transition in the MENA area, this level of study emphasizes the necessity for comprehensive solutions that address both the technological and socio-political difficulties [18,19].

### *Previous Research on Sustainable Supply Chain Capabilities*

**Multi-Criteria Decision-Making (MCDM) Approaches:**

The Analytical Hierarchy Process (AHP) and the Analytical Network Process (ANP), two MCDM techniques, have been extensively used to evaluate supply chain performance. AHP was used by Fernandez-Vazquez et al. (2015) to assess supply chain sustainability, showing that it is capable of managing a variety of factors [20]. Fuzzy AHP was also used by Shete et al. (2020) to evaluate green supply chain management strategies, demonstrating its usefulness in handling difficult decision-making situations [21].

Ordu and Der (2023) propose a hybrid multi-criteria decision-making (MCDM) model to select appropriate polymeric materials for manufacturing flexible pulsating heat pipes, emphasizing the critical role of material selection in fluidic system design. The study evaluates twelve thermoplastic alternatives against fourteen criteria using three MCDM methods, namely AHP-GRA, AHP-CoCoSo, and AHP-VIKOR. The results indicate that polytetrafluoroethylene (PTFE), polyethylene (PE), and polypropylene (PP) are the top choices, with PTFE being the most suitable due to its excellent mechanical and thermal properties. This research provides a systematic approach to material selection, beneficial for industry professionals and academics in the field [22].

Yalçın et al. (2023) investigate the optimization of micro-drilling parameters for aluminum–polyethylene composite panels (Al–PE) using Taguchi's L16 orthogonal array design, linking their findings to multi-criteria decision-making (MCDM) methods. The study assesses multiple performance metrics—thrust force, burr formation, tool wear, and hole diameters—critical in evaluating machining efficiency. By employing five control parameters, including cutting speed, feed rate, tool diameter, tool point angle, and tool coating, the researchers applied analysis of variance (ANOVA) to identify significant factors influencing drilling performance. Notably, the tool point angle had the greatest impact on thrust force (64.54%) and burr height (67.80%), while cutting speed significantly affected hole diameter changes (25.15%). These results can inform MCDM frameworks by providing quantitative data to prioritize machining conditions that minimize thrust, burr height, and diameter variations. The study's insights contribute to developing a robust decision-making process in manufacturing settings, emphasizing the need for optimizing multiple conflicting criteria [23].

**Fuzzy Logic and Expert Systems:**

A common technique for managing the ambiguities and uncertainties present in supply chain evaluations is fuzzy logic. Fuzzy sets were first used to model uncertainty by Ahmad and John (2023), and supply chain management has since widely used them [24]. Afrasiabi et al. (2022) evaluated supplier performance using a fuzzy expert system, providing a strong foundation for handling ambiguous information in decision-making [25].

**Application of ANFIS and FIS:**

Utilizing Fuzzy Inference Systems (FIS) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), supply chain assessments have become more accurate and dependable. ANFIS, which models complex systems by fusing fuzzy logic and neural networks, was introduced by Hamidzadeh et al. (2023) [26]. ANFIS was used by Okwu et al. (2020) to evaluate supplier sustainability in the context of supply chain management, demonstrating its promise in this domain [27].

**Simulation and Validation Using MATLAB and Simulink:**

Mathematical models in supply chain management are frequently simulated and validated using MATLAB and Simulink. For the purpose of developing and evaluating complicated assessment models, Sarir and Abderhmane (2022) offer extensive modeling, simulation, and analysis tools [28]. For instance, Li-ma-Junior and Ribeiro Carpinetti (2020) demonstrated how successful MATLAB is in validating theoretical models by simulating supply chain performance [29].

Furthermore, several other studies have been conducted in this area, outlined as follows: Govindan et al. (2021) conducted a study on supply chain management and corporate social responsibility, developing a hierarchical framework for supply chain management. They introduced a multi-faceted measurement scale to illustrate specific management practices within the supply chain domain [30]. Recognizing the significance of reverse supply chains for a sustainable economy, product recycling, and green initiatives, Fadhel (2021) developed a model for a multi-tier closed-loop green supply chain network. This model meets market demand by managing factors such as the cost of lost sales while ensuring that employee exposure to harmful chemicals in the workplace remains within standard safety limits [31]. Fu et al. (2022), drawing on the theory of organizational information processing, demonstrated that the impact of suppliers and customers on operational performance varies across different production systems, such as single-type production, manual production, and mass production systems. Their experimental findings also revealed how integrating suppliers and customers can be aligned with various production system configurations to achieve optimal quality, flexibility, delivery, or cost performance [32]. Frederico et al. (2020) demonstrated that modifications in quality improvement programs, considered the most fundamental aspect of the balanced scorecard dimensions, significantly impact indicators such as employee skills, customer satisfaction, non-conforming products, and profit, which span across all levels of the balanced scorecard [33]. Ardakani et al. (2024) highlighted that, despite the growing importance and increasing share of the service sector in the global economy, research on service sector supply chains remains scarce compared to the industrial sector. This scarcity is attributed to inherent challenges in developing standard supply chain models and the complexity of designing and delivering service processes [34]. Yousefi et al. (2022) evaluated sustainable supply chain management practices [35]. Sangaiah et al. and Omidari (2020) developed a mathematical model for designing the crude oil supply chain, addressing issues related to facility location, demand allocation, transportation, and distribution planning [36]. Bamakan et al. (2021) created a model for evaluating the performance of product–service supply chains and validated its accuracy through expert consensus using the fuzzy Delphi method. Subsequently, they developed a performance measurement system utilizing neural networks [37]. Kaviani et al. (2020) emphasized that the evolving dynamics of global trade necessitate supply chains' ability to adapt to change. They also highlighted that the complexity of the business environment and heightened competition across industries contribute to instability in competitive factors. Sustaining and enhancing competitiveness demands organizational competencies that generate customer value through organizational capabilities [38]. Khalilpourazari et al. (2023) proposed a mixed nonlinear programming mathematical model for optimizing the blood supply chain, aiming to minimize costs and mitigate shortages of blood products [39].

From the initial studies, Table 1 outlines the identified supply chain capabilities and research gaps.

**Table 1.** Research conducted on sustainable supply chain capabilities.

| Model | Economic Capability | Environmental Capability | Social Capability | Model | Economic Capability | Environmental Capability | Social Capability |
|---|---|---|---|---|---|---|---|
| [1] | * | | | [24] | * | | |
| [2] | | * | | [25] | * | * | |
| [3] | * | | | [27] | * | * | |
| [5] | * | | | [28] | * | | |
| [7] | | * | * | [29] | * | | |
| [8] | | * | * | [30] | | * | * |
| [9] | * | * | | [31] | | * | |
| [11] | * | | | [32] | * | | |
| [12] | * | | | [33] | * | | |
| [18] | * | * | | [34] | | * | |
| [19] | * | * | | [35] | * | | |
| [20] | * | * | | [38] | * | | |
| [21] | * | * | | [39] | * | | |

(*) indicate the presence of the model in the mentioned references.

Based on the conducted studies, most research in the field has been one-dimensional. Typically, these studies have examined technological capabilities, production capabilities, supply capabilities, or other capabilities individually or in isolated case studies. Consequently, there appears to be a lack of a comprehensive model that integrates these capabilities and provides a mathematical framework for them. Given these findings, the primary focus of this research is to propose a model for assessing multiple capabilities within sustainable supply chains.

## 3. Methodology

For the purpose of conducting the present research, initial steps involve identifying the capabilities inherent to a sustainable supply chain. Subsequently, the frameworks for evaluating these capabilities are structured. Following this, the definitive model for sustainable supply chain capabilities is formulated, culminating in the validation of this model in the final step. Concluding the findings is also integral to the fifth step of the process.

In order to explore and evaluate the multiple capabilities within a sustainable supply chain, there is a recognized need to develop a comprehensive mathematical model capable of the simultaneous assessment of these capabilities. This research endeavors to address this requirement by presenting a structured framework and advancing a model tailored to this specific issue.

### 3.1. Multi-Criteria Assessment Clarification

The objective of this study is to evaluate the supply chain using a multi-criteria approach, where each criterion is assigned a weight that reflects its importance in the overall assessment. These weights were established through the Analytic Hierarchy Process (AHP), ensuring they are grounded in expert opinions and tailored to the specific context of the energy sector. This weighting process enhances the usability of the results by providing a customized assessment that aligns with industry priorities. The final value derived from the assessment represents a weighted aggregation of performance across all criteria, offering a comprehensive understanding of the supply chain's capabilities. This nuanced evaluation aids in identifying strengths and weaknesses, thereby guiding decision makers in strategic planning and resource allocation.

The data collection process employs qualitative methodologies such as meetings, interviews, and questionnaires involving academic and industrial experts in the energy sector. These methods aim to identify the foundational components of the research and utilize the fuzzy Delphi technique to screen key decision-making indicators.

### 3.2. Rationale for Choosing Fuzzy Expert Systems

In this study, we chose fuzzy expert systems over other multi-criteria decision-making (MCDM) methods, such as Analytic Hierarchy Process (AHP) and Adaptive Neuro-Fuzzy Inference System (ANFIS), for several reasons pertinent to the context of Iran's energy sector, detailed as follows:

Handling Uncertainty and Vagueness: The energy sector in Iran is characterized by significant uncertainties, including fluctuating market conditions and regulatory changes. Fuzzy expert systems excel at managing uncertainty by accommodating imprecise and vague information common in qualitative assessments.

The Integration of Expert Knowledge: These systems facilitate the incorporation of expert opinions into the decision-making process. Given the critical role of local expertise in addressing the specific challenges of the Iranian energy landscape, our methodology emphasizes the importance of integrating insights from industry professionals.

Comprehensive Evaluation: Unlike AHP and ANFIS, fuzzy expert systems provide a holistic framework for evaluating multiple criteria simultaneously. This approach enables the consideration of both quantitative and qualitative data, allowing for a more nuanced analysis of supply chain capabilities.

Flexibility and Adaptability: The framework offers flexibility, adapting to the unique needs of various stakeholders in the energy sector. This adaptability is crucial for addressing the differing operational priorities and challenges faced by companies in Iran.

Previous Successful Applications: The successful application of fuzzy expert systems in similar contexts underscores their effectiveness in enhancing decision-making processes. This historical precedent reinforces our decision to adopt this approach in our research.

### 3.3. Input Data

Case studies are conducted to demonstrate the efficiency of the proposed model in a three-level supply chain that includes manufacturers, distribution centers, and customers. The input data for this supply chain are collected from several sources, including related articles and real industry data. For instance, production costs, transportation costs, customer demand, and facility capacities are obtained from these sources.

Demand information and facility capacities are presented in the form of fuzzy numbers to reflect uncertainties in forecasting processes. Additionally, the greenhouse gas emissions associated with various supply chain activities are measured per unit of product and included in the model. Coefficients related to renewable energies and carbon emission reductions are also estimated based on reliable sources and previous studies.

In this study, data were collected through surveys and interviews with experts from 16 companies in Iran's energy sector. The input data include both objectively measurable variables and subjective evaluations, allowing for a comprehensive evaluation of sustainable supply chain capabilities.

Objectively measurable variables: These consist of quantitative metrics such as production output, financial performance, energy consumption, and environmental impact (e.g., carbon emissions), which can be directly quantified and compared.

Subjective evaluations: Experts provided qualitative assessments related to aspects such as innovation, technological advancement, organizational adaptability, and resilience. These aspects, while difficult to quantify, are critical for a holistic evaluation of supply chain capabilities.

The combination of objective and subjective data was processed through a fuzzy expert system, designed to manage uncertainty and the complexity inherent in qualitative judgments. To ensure the accuracy and relevance of the data, experts were asked to evaluate only their own companies. This approach minimizes potential bias that might arise from cross-company assessments, as experts are most familiar with the internal dynamics and specific challenges of their organizations. This method also ensures that the data reflect each company's unique context within the energy sector.

Iran's energy industry is widely acknowledged as one of the largest and most pivotal sectors, both in the Middle East and globally. With abundant reserves of oil and gas, Iran ranks prominently in the global production and export of these resources. As one of the top five global producers of oil, Iran plays a critical role in meeting global energy demands, annually producing millions of barrels of oil. Moreover, Iran possesses substantial reserves of natural gas and is recognized as a major global producer and exporter of gas. These strategic advantages, coupled with significant potential in electricity generation from hydroelectric, solar, and wind power sources, position Iran as a crucial player in regional and global energy markets. The supply chain, as an integral component of the energy industry, assumes paramount importance. This study aims to investigate methodologies for assessing supply chain capabilities, particularly within the energy sector.

The assessment of sixteen businesses involved in Iran's energy sector falls inside the study's geographical purview. A total of thirty-five specialists were selected according to particular monitoring feature requirements. The techniques used for gathering data included surveys, interviews, and analytical techniques such fuzzy expert systems, fuzzy Delphi methods, and simulations. In order to guarantee a thorough and accurate examination of Iran's energy industry, these businesses were selected based on a number of important factors. The principal standards comprised the following:

Operational Scale and Influence: in order to gather a broad range of skills and practices, companies having a substantial operational scale and influence in the energy industry were given preference.

Variety in Energy Subsectors: to guarantee different viewpoints and thorough insights, we included businesses from a range of energy industry subsectors, including oil, gas, and renewable energy.

Data Accessibility: a critical component of our analysis's validity and robustness, companies were chosen based on our capacity to obtain accurate, detailed data.

Expertise and Willingness to Participate: to guarantee that the data gathered were both pertinent and of the highest caliber, we took into account the representatives of the companies' expertise as well as their willingness to take part in the study.

Our concept was successfully implemented in the energy sector due to the industry's strong information accessibility. It is worth remembering that the developed model is flexible and applicable to other businesses, not just the energy sector. To confirm and broaden the model's usefulness, future research could duplicate a similar strategy in other industries.

### *3.4. Data Analysis and Exploration*

First fuzzy expert subsystems are designed to represent and evaluate different capacities within a sustainable supply chain. These subsystems include technological innovation, resilience capabilities, competitiveness, and operational efficiency, as determined by study. The four fuzzy expert subsystems produce outputs that are utilized as input variables in the comprehensive expert system. This allows for various degrees of assessment to be conducted across the varied capacities of the sustainable supply chain.

### *3.5. Understanding Fuzzy Logic in Sustainable Supply Chain Assessment*

Introduced by Zadeh in 1965, fuzzy logic is a type of many-valued logic that deals with approximations in reasoning as opposed to precise and fixed inference. Unlike classical binary sets, where variables must be either true or false, fuzzy logic variables can have a truth value ranging between 0 and 1. This makes it an ideal tool for handling uncertainty and imprecision. In our research, we use fuzzy logic to model and assess various sustainable supply chain capabilities. The fuzzy expert subsystems we developed use linguistic variables (such as low, medium, and high) to describe input parameters, which are then processed through a set of defined rules to produce output assessments. This approach allows for a nuanced evaluation of capabilities like competitiveness, operational efficiency, technological advancement, and resilience, accommodating the inherent variability and complexity of real-world supply chain scenarios.

The modeling of the fuzzy expert subsystem aimed at evaluating competitiveness capabilities draws upon theoretical studies. The key input variables identified include product quality, financial and economic performance, and product innovation, each assessed through nine linguistic variables. Figure 1 illustrates the methodology employed by the fuzzy expert subsystem in evaluating competitiveness capabilities.

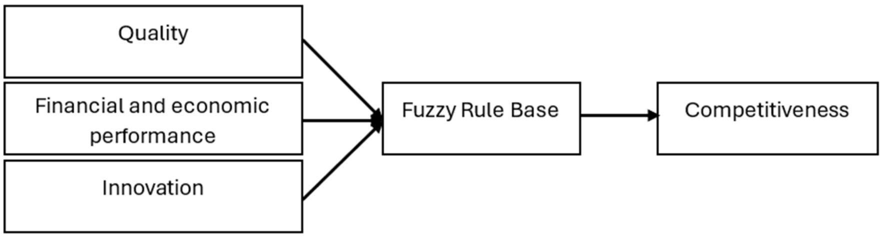


**Figure 1.** Fuzzy expert subsystem for evaluating competitive capability.

Table 2 presents the input variables expressed as percentages, linguistic values for these variables, and their corresponding fuzzy numbers used in the assessment of competitiveness.

**Table 2.** Linguistic values of input variables for competitiveness assessment.

| Variable | Symbol of Linguistic Values | Fuzzy Numbers |
|---|---|---|
| Product Quality | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Financial and Economic | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Product Innovation | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |

Using the input variables and established rules, three levels have been defined for evaluating the output variable. The consensus among experts has been quantified using trapezoidal fuzzy numbers to represent the output variable values of the system. These results are summarized in Table 3.

**Table 3.** Competitiveness performance evaluation output variable.

| Output Variable | Symbol | Fuzzy Numbers |
|---|---|---|
| Product Quality | C1 | [0%, 0%, 10%, 40%] |
| | C2 | [20%, 40%, 60%, 80%] |
| | C3 | [60%, 90%, 100%, 100%] |

In this phase, a fuzzy rule base was established utilizing input linguistic variables and expert opinions, comprising 30 "if-then" rules. The output of the three-dimensional model depicting competitiveness is depicted in Figure 2.

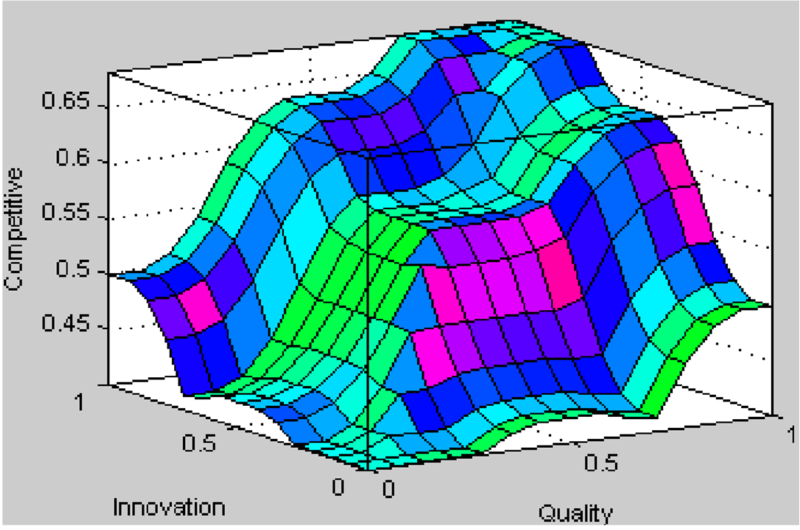


**Figure 2.** Three-dimensional model output of competitiveness performance.

### 3.6. Modeling the Fuzzy Expert Subsystem for Evaluating Operational Capability

Based on a review of the theoretical foundations in this research, input variables including logistics, social factors, and environmental variables have been identified for assessing operational capability. Additionally, nine linguistic variables have been defined to measure these inputs comprehensively. The design of the fuzzy expert subsystem aimed at evaluating operational capability is illustrated in Figure 3.

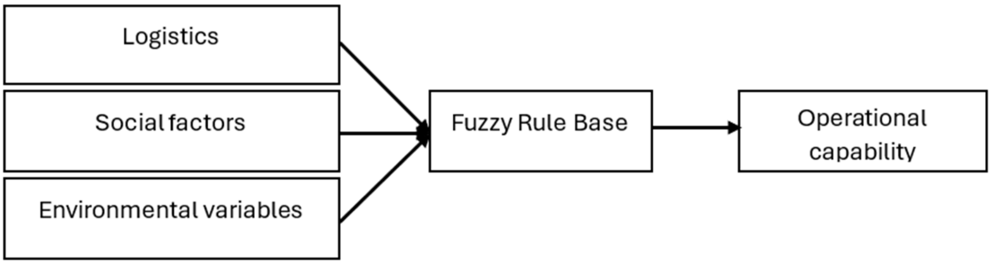


**Figure 3.** Fuzzy expert system for operational capability assessment.

Figure 3 illustrates the fuzzy expert system for operational capability assessment. It highlights the key input variables, including logistics, social factors, and environmental considerations, which are vital for evaluating operational efficiency. This visual representation helps clarify the interconnections among these factors.

Table 4 presents the input variables expressed as percentages, linguistic values for operational factors, and their corresponding specialized fuzzy numbers.

Based on the input variables and formulated rules, 3 levels were defined to evaluate the output variable. The experts' average opinion has been determined in the form of trapezoidal fuzzy numbers as the output variable value of the system, the results of which can be seen in Table 5.

**Table 4.** The linguistic values of input variables for operational capability assessment.

| Variable | Symbol of Linguistic Values | Fuzzy Numbers |
|---|---|---|
| Logistics | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Social factors | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Environmental factors | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |

**Table 5.** The linguistic values of the operational capability assessment output variable.

| Output Variable | Symbol | Fuzzy Numbers |
|---|---|---|
| Operational Capability Assessment | O1 | [0%, 0%, 10%, 40%] |
| | O2 | [20%, 40%, 60%, 80%] |
| | O3 | [60%, 90%, 100%, 100%] |

In this phase, the fuzzy rule base was developed by utilizing input linguistic variables and incorporating experts' opinions through 30 "if-then" rules. The output of the three-dimensional operational capability model is depicted in Figure 4.

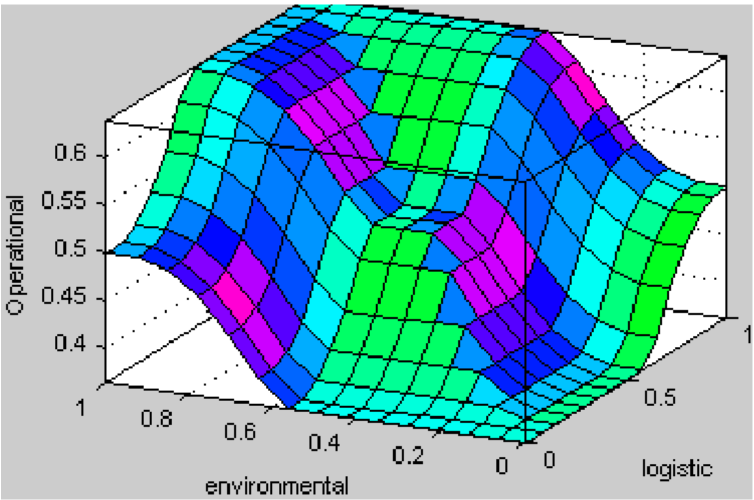


**Figure 4.** Three-dimensional model output of operational capability.

### *3.7. Fuzzy Expert Subsystem Modeling for Technology Capability Assessment*

Drawing upon a thorough exploration of the research's theoretical underpinnings, two variables—research and development, and construction and production—have been pinpointed as input variables for assessing technology capability. Additionally, six linguistic variables have been defined to gauge this capability. The design of the fuzzy expert subsystem for evaluating technology capability is depicted in Figure 5.

Figure 5 presents the fuzzy expert system designed for technology capability assessment. It serves to visually communicate the essential input variables, such as research and development, which are critical for enhancing technological capabilities in the energy sector.

Input variables and linguistic values of technology evaluation input variables along with specialized fuzzy numbers can expressed as percentages in Table 6.

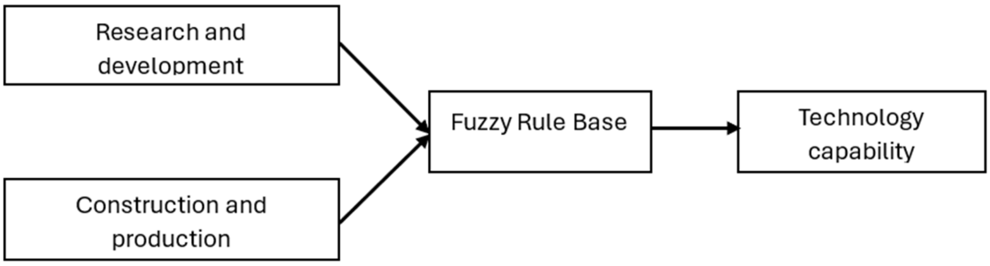


**Figure 5.** Fuzzy expert system for technology capability assessment.

**Table 6.** The linguistic values of the input variables for technology capability assessment.

| Variable | Symbol of Linguistic Values | Fuzzy Numbers |
|---|---|---|
| Research and development | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Construction and production | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |

Based on the defined input variables and formulated rules, three levels have been established for evaluating the output variable. The experts' average opinions are quantified as the output value of the system using trapezoidal fuzzy numbers, and the outcomes are detailed in Table 7.

**Table 7.** Technology capability assessment.

| Output Variable | Symbol | Fuzzy Numbers |
|---|---|---|
| Technology Capability Assessment | V1 | [0%, 0%, 10%, 40%] |
| | V2 | [20%, 40%, 60%, 80%] |
| | V3 | [60%, 90%, 100%, 100%] |

In this phase, the fuzzy rule base was developed by integrating input linguistic variables and expert opinions, employing 15 "if-then" rules as outlined in the second section. Figure 6 illustrates the output of the three-dimensional model depicting technological capabilities.

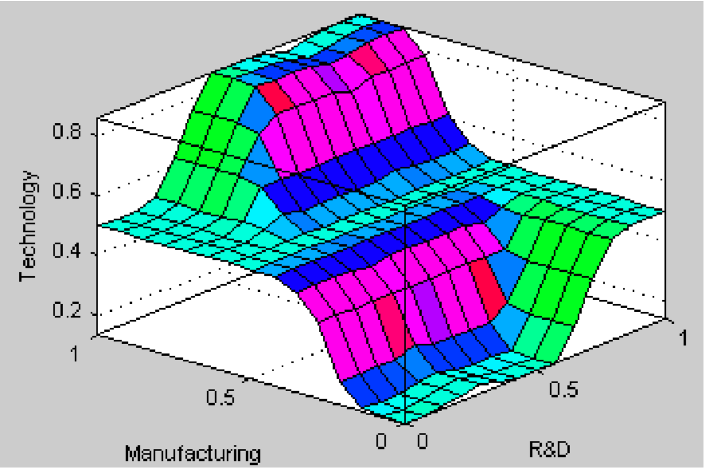


**Figure 6.** Three-dimensional model output of technology capability.

### 3.8. Fuzzy Expert Subsystem Modeling of Resilience Capability

According to the theoretical foundations studied in the research, the fuzzy expert subsystem for modeling resilience capability identified three input variables: flexibility, adaptability, prediction, and environmental analysis. Additionally, nine linguistic variables were identified to assess this capability. The design of the fuzzy expert subsystem for evaluating resilience capability is illustrated in Figure 7.

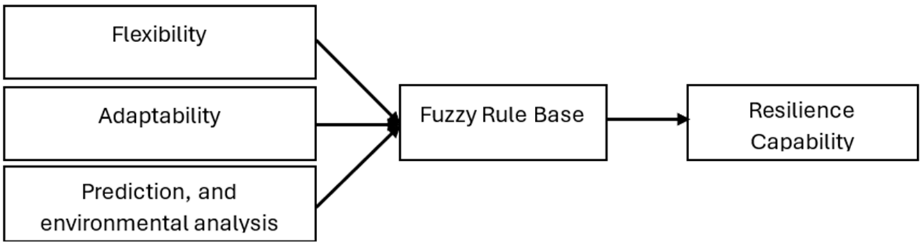


**Figure 7.** Fuzzy expert system for resilience capability assessment.

Figure 7 depicts the fuzzy expert system for resilience capability assessment. This figure emphasizes the importance of flexibility, adaptability, and predictive analysis in fostering resilient supply chains, particularly within the dynamic context of Iran's energy sector.

Table 8 presents the input variables expressed as percentages, their linguistic values, resilience factors, and corresponding fuzzy numbers.

**Table 8.** The linguistic values of the input variables for resilience capability assessment.

| Variable | Symbol of Linguistic Values | Fuzzy Numbers |
|---|---|---|
| Flexibility | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Adaptability | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Prediction, and environmental analysis | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |

Based on the input variables and the established rules, three levels have been defined to assess the output variable. The experts' consensus, expressed as trapezoidal fuzzy numbers, represents the system's output variable value, with detailed results provided in Table 9.

**Table 9.** The linguistic values of the output variable for resilience capability assessment.

| Output Variable | Symbol | Fuzzy Numbers |
|---|---|---|
| Resilience Capability Assessment | R1 | [0%, 0%, 10%, 40%] |
| | R2 | [20%, 40%, 60%, 80%] |
| | R3 | [60%, 90%, 100%, 100%] |

In this phase, a fuzzy rule base was established utilizing input linguistic variables and expert insights, comprising 30 "if-then" rules. The output of the three-dimensional resilience capability model is depicted in Figure 8.

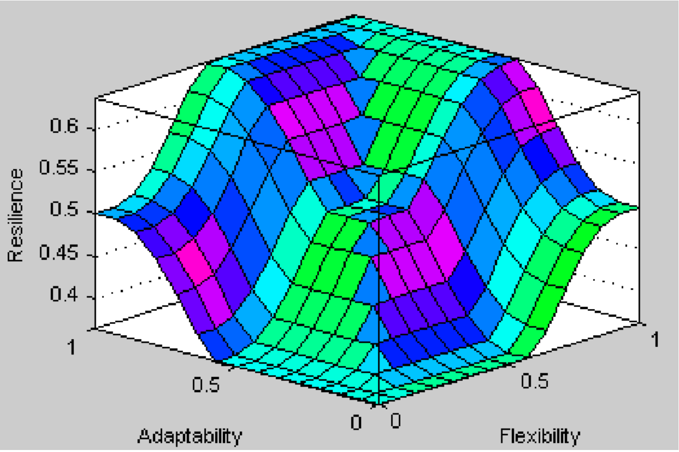


**Figure 8.** Three-dimensional model output of resilience capability.

### 3.9. Final Modeling of the Sustainable Supply Chain Capabilities System

Based on the fuzzy expert system modeling, the determination of sustainable supply chain capabilities, encompassing competitiveness, operational efficiency, technology, and resilience in this domain, is achieved through final system modeling. Thus, considering the essential concepts, variables such as the competitiveness, operational efficiency, technology, and resilience capabilities of the sustainable supply chain are designated as input variables, while the level of sustainable supply chain capabilities is defined as the output variable. The design of the fuzzy expert system for sustainable supply chain capabilities is illustrated in Figure 9.

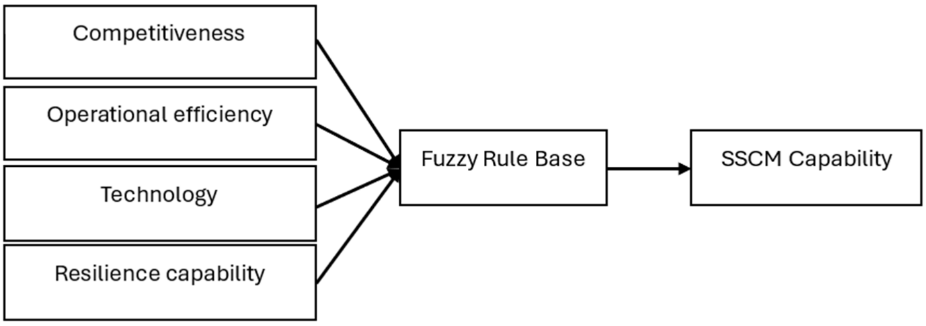


**Figure 9.** Fuzzy expert system for sustainable supply chain capabilities.

Figure 9 outlines the fuzzy expert system for assessing sustainable supply chain capabilities. It integrates the various dimensions of competitiveness, operational efficiency, technology, and resilience, providing a comprehensive overview of the sustainable supply chain model developed in this study.

Table 10 presents the input variables expressed as percentages, their linguistic values, and the corresponding fuzzy numbers assigned to the system's input variables.

**Table 10.** Linguistic values of input variables.

| Variable | Symbol of Linguistic Values | Fuzzy Numbers |
|---|---|---|
| Competitiveness | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Operational efficiency | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Technology | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |
| Resilience capability | Low | [0%, 0%, 10%, 40%] |
| | Medium | [20%, 40%, 60%, 80%] |
| | High | [60%, 90%, 100%, 100%] |

Based on the input variables and the formulated rules, three levels have been established to assess the output variable. The experts' consensus average is represented as trapezoidal fuzzy numbers, indicating the system's output variable value, with detailed results available in Table 11.

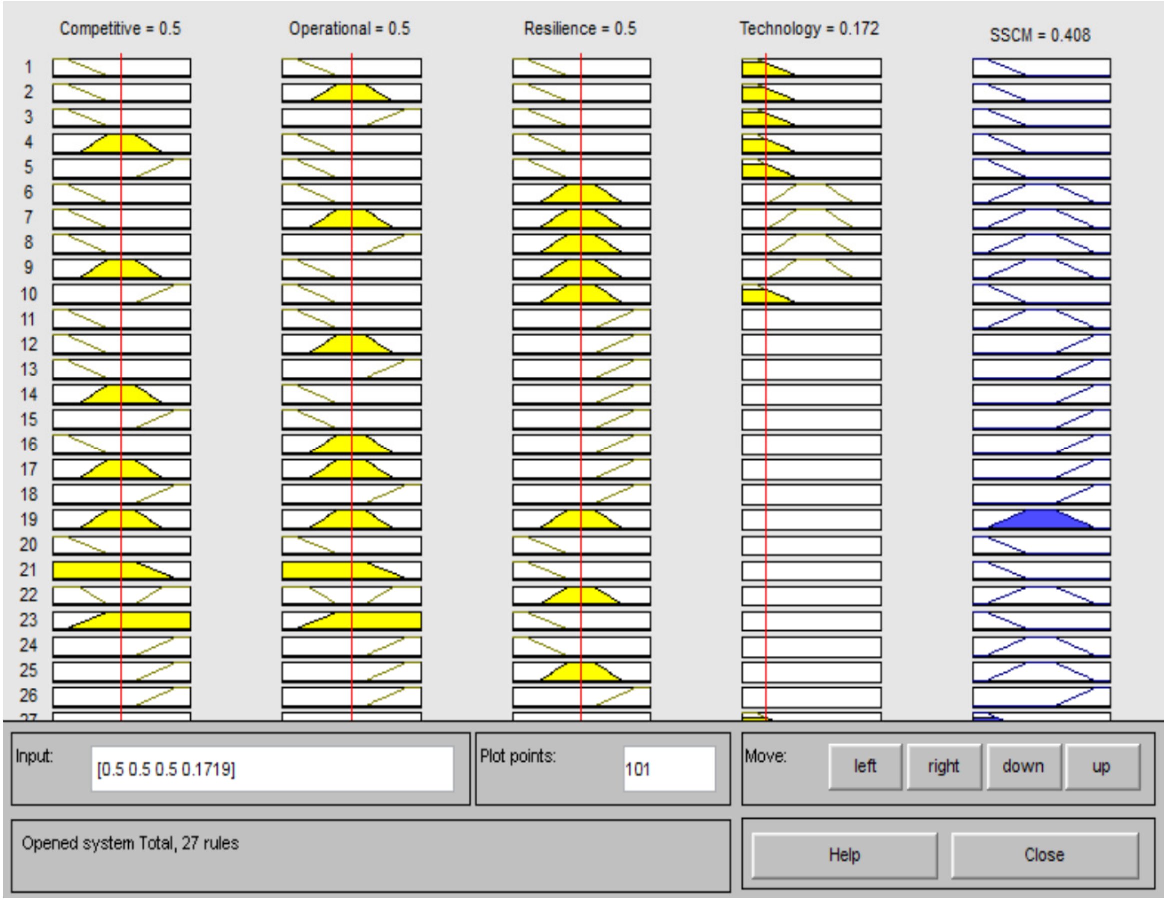
**Table 11.** The linguistic values of output variables for sustainable supply chain capabilities.

| Output Variable | Symbol | Fuzzy Numbers |
|---|---|---|
| Capabilities of Sustainable Supply Chain | SSCM 1 | [0%, 0%, 10%, 40%] |
| | SSCM 2 | [20%, 40%, 60%, 80%] |
| | SSCM 3 | [60%, 90%, 100%, 100%] |

In this phase, the fuzzy rule base was constructed using input linguistic variables and expert opinions, comprising 84 "if-then" rules, as detailed in the preceding section. Following the design and definition of fuzzy rules based on the system's input and output variables, the final model was derived, depicted in Figures 10–12.

### *3.10. Validation of Expert Systems*

An expert system's design process requires validation to guarantee the accuracy of its results and performance. Data from several case samples were fed into the model during model validation, and the outputs that came out were graded. Experts then assessed the results in light of their expertise. A high success rate of more than 84% was found when the system's results were compared to the evaluations conducted in person.



Competitive = 0.5

Operational = 0.5

Resilience = 0.5

Technology = 0.172

SSCM = 0.408

Input: [0.5 0.5 0.5 0.1719]

Plot points: 101

Opened system Total, 27 rules

**Figure 10.** Decision rules output of fuzzy expert system for sustainable supply chain capabilities.

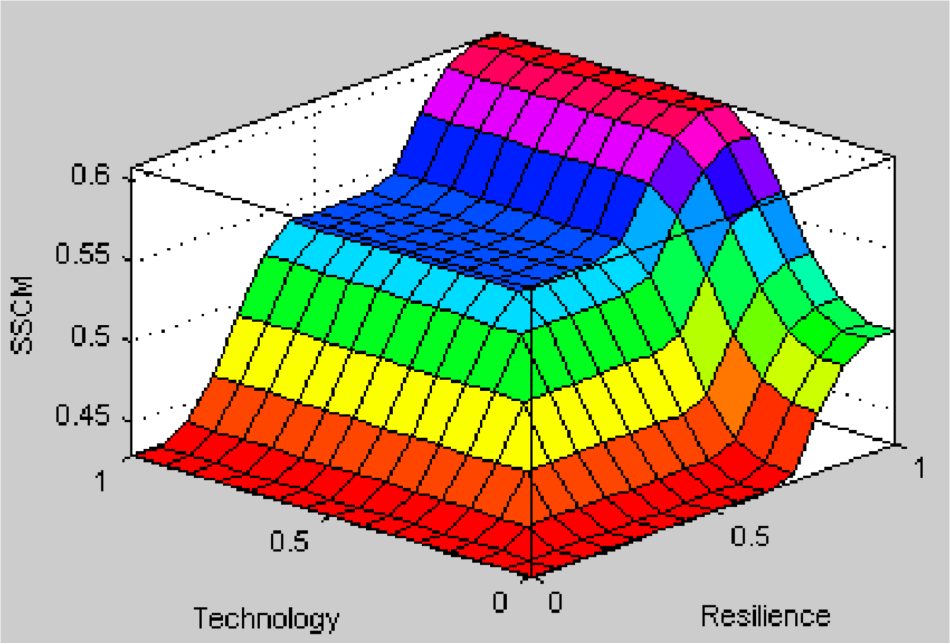


**Figure 11.** Three-dimensional output of fuzzy expert system for sustainable supply chain capability 1.

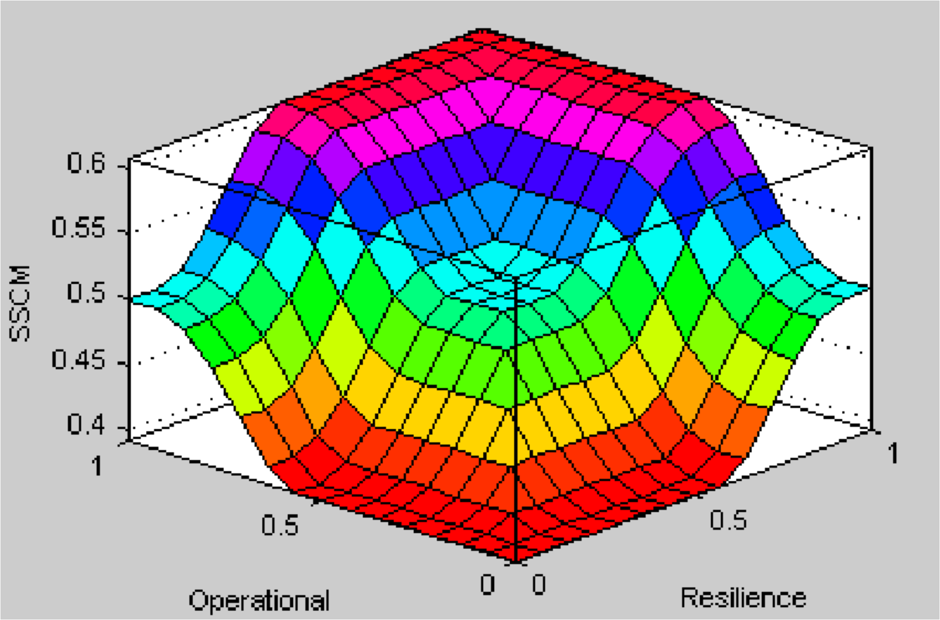


**Figure 12.** Three-dimensional output of fuzzy expert system for sustainable supply chain capability 2.

### *3.11. Expert Validation Process*

The expert validation process was crucial for ensuring the accuracy and reliability of the fuzzy expert system. A panel of experts was selected, consisting of professionals with a minimum of 10 years of experience in the Iranian energy sector, encompassing diverse domains such as operations, technology, and management. This diversity allowed for a comprehensive evaluation of sustainable supply chain capabilities.

The validation involved presenting the model to the panel, who provided feedback on the relevance and accuracy of the criteria, weights, and evaluations. The sample data used for validation were sourced from multiple reputable organizations in Iran's energy sector, ensuring that the data reflected a variety of real-world scenarios. The organizations varied in size and operational focus, enhancing the representativeness of the sample.

The validation process achieved an accuracy rate of over 84%, demonstrating a strong alignment between the model's predictions and expert evaluations. This high accuracy underscores the credibility of the fuzzy expert system in assessing sustainable supply chain capabilities.

## 4. Discussion

Using fuzzy expert systems, this study offers a comprehensive assessment of the sustainable supply chain capabilities in Iran's energy industry. Through the examination of four key dimensions—competitiveness, operational efficiency, technology, and resilience—the study seeks to provide in-depth understandings of the ways in which these elements impact supply chain performance in the Iranian energy sector. This section will examine the findings, go over their ramifications, and offer suggestions specific to Iran's energy industry.

### *4.1. Recommendations Based on Model Results*

The following recommendations will be included in the Results and Discussion section of the manuscript:

Identifying Weakest Areas: Each company's assessment will result in distinct scores for each criterion evaluated by the fuzzy logic model. The lowest scores will indicate areas where the company is underperforming relative to others in the energy sector.

Specific Focus Areas:

- Operational Efficiency: If a company scores low in operational efficiency, we recommend that they conduct a thorough review of their logistics processes. This may

involve investing in technologies that improve inventory management and transportation optimization to reduce costs and enhance service levels.
- Technological Advancements: Should the assessment highlight deficiencies in technological capabilities, it would be beneficial for the company to prioritize investments in research and development. Collaborations with tech firms or academic institutions could foster innovation and introduce advanced technologies into their operations.
- Resilience and Adaptability: For companies demonstrating weak resilience scores, we suggest developing risk management strategies. This could include scenario planning and training programs aimed at enhancing flexibility in operations to better handle disruptions.

Action Plan Development: Based on the weakest contributions identified, organizations should formulate an action plan that specifies measurable objectives and timelines for improvement. This action plan can be guided by the aggregated insights of the fuzzy logic model, providing a clear roadmap for targeted enhancements.

### *4.2. Operational Recom Resilience Capabilitymendations for Enhancing Supply Chain Sustainability*

Based on the findings related to competitiveness, operational efficiency, technology, and resilience, we provide the following specific recommendations for companies in the Iranian energy sector to improve their supply chain sustainability:

Enhancing Competitiveness:

- Conduct regular market analyses to identify trends and adjust business strategies accordingly.
- Establish collaborations and partnerships to access new technologies and markets.

Improving Operational Efficiency:

- Implement lean management practices to streamline processes and reduce waste.
- Utilize data analytics tools for real-time monitoring and informed decision-making.

Leveraging Technology:

- Invest in smart technologies (IoT and AI) to enhance supply chain visibility and automation.
- Encourage R&D investments focused on developing sustainable practices and technologies.

Building Resilience:

- Conduct thorough risk assessments to identify vulnerabilities in supply chains.
- Diversify the supplier base to mitigate risks associated with potential disruptions.

### *4.3. Analysis of Fuzzy Expert Systems Results*

Several important discoveries are highlighted by the modeling of fuzzy expert subsystems for assessing sustainable supply chain capabilities.

Ability to Compete: A fuzzy expert system integrates factors including innovation, financial performance, and product quality to determine a company's competitiveness. Expert opinions can be represented using trapezoidal fuzzy numbers, which enable a more complex understanding of competitiveness. The results, which are summed up in Table 3, demonstrate a strong relationship between improved competitiveness and increased innovation, good financial performance, and high product quality. Companies in the Iranian energy sector who score highly in these categories are better positioned to improve their market status, as shown by the three-dimensional model output (Figure 2). This outcome emphasizes that in order to maintain a competitive advantage in both domestic and foreign markets, Iranian energy companies must concentrate on improving the quality of their products, their financial stability, and their innovative methods.

Operational Capability: Logistics, social concerns, and environmental considerations are all taken into account while evaluating operational capability. As demonstrated in Table 5, fuzzy logic enables a detailed evaluation of these components, revealing that effective logistics, favorable social conditions, and strong environmental practices significantly boost operational efficiency. The three-dimensional model output (Figure 4) reinforces the importance of optimizing these areas to achieve superior operational performance. For Iran's energy sector, this implies that improvements in logistics infrastructure, social dynamics, and environmental stewardship are crucial for building a more resilient and efficient supply chain.

Technology Capability: Evaluating technology capability focuses on research and development (R&D) and construction and production processes. The results presented in Table 7 indicate that higher R&D investments and advanced construction techniques enhance technological capability. The model output (Figure 6) illustrates that for Iranian energy companies, investing in cutting-edge technology and advancing construction practices are vital for maintaining competitiveness and driving innovation. This finding aligns with the broader understanding that technological advancements are key to sustainable supply chain performance, especially in a sector as dynamic as energy.

Resilience Capability: The resilience capability assessment incorporates variables such as flexibility, adaptability, prediction, and environmental analysis. As shown in Table 9, higher scores in these areas contribute to greater resilience. The output of the three-dimensional model (Figure 8) highlights the importance of these factors in enabling supply chains to navigate uncertainties and disruptions. For Iran's energy sector, developing robust strategies to enhance flexibility and adaptability is essential for managing potential disruptions and ensuring continuity.

### *4.4. Rationale for Selected Factors and Additional Dimensions of Resilience*

The fuzzy model for resilience capability focuses on four key factors, namely flexibility, adaptability, prediction, and environmental analysis. These factors were chosen based on their critical importance in enabling organizations in Iran's energy sector to navigate uncertainties and enhance operational resilience.

Flexibility: enables organizations to respond swiftly to changes in the operating environment, essential in a sector characterized by market fluctuations and regulatory shifts.

Adaptability: emphasizes the ability to evolve in response to new technologies and market demands, positioning companies to implement innovative solutions.

Prediction: highlights the importance of forecasting potential disruptions, allowing proactive strategy development to mitigate risks.

Environmental Analysis: stresses the significance of understanding external factors impacting supply chain resilience, crucial given Iran's geopolitical and economic context.

In addition to these factors, several other dimensions of resilience are relevant for the Iranian energy sector:

Supply Chain Diversity: reducing dependency on single sources enhances resilience against disruptions.

Collaborative Networks: establishing relationships across the sector fosters knowledge sharing and problem-solving.

Resource Availability: ensuring access to critical resources is fundamental for maintaining operational capacity.

Technological Innovation: investment in technology significantly improves resilience by optimizing processes and enhancing decision-making.

### *4.5. Implications for Sustainable Supply Chain Management*

The integration of fuzzy expert systems into the evaluation of supply chain capabilities provides several significant implications for Iran's energy sector:

Enhanced Precision in Assessment: Fuzzy logic offers a more precise and flexible approach to assessing supply chain capabilities compared to traditional methods. By accounting for uncertainty and expert opinions, fuzzy systems provide a more accurate depiction of performance and capabilities, which is particularly valuable in the complex and variable landscape of Iran's energy sector.

Strategic Focus Areas: The results emphasize key strategic areas for improvement. For Iranian energy companies, prioritizing investments in competitiveness, operational efficiency, technology, and resilience can lead to substantial performance enhancements. Companies should focus on these areas to develop a more sustainable and effective supply chain.

Industry-Specific Applications: While the study primarily targets the energy sector, the methodology and findings can be adapted for broader applications. Other industries within Iran can leverage similar fuzzy expert systems to assess and improve their supply chain capabilities, adjusting the models to meet industry-specific needs and challenges.

Validation of Expert Systems: The high success rate of over 84% in the validation results confirms the reliability of the fuzzy expert system in providing accurate assessments. This validation supports the model's applicability in real-world scenarios, reinforcing its relevance for practical use in Iran's energy sector.

### *4.6. Practical Applications of Results*

The results obtained from the multi-criteria assessment serve as a valuable tool for organizations in the energy sector to enhance decision-making and strategic planning.

Individual Category Insights: The scores for each evaluated category allow decision makers to identify specific areas of strength and weakness, facilitating targeted initiatives. For instance, low operational efficiency scores may prompt management to focus on logistics improvements and process optimization strategies.

Overall Summary Number: The aggregate performance score provides a quick overview of the supply chain's overall health and can be used for benchmarking against industry standards. This number helps stakeholders understand the relative position of the organization within the competitive landscape.

Data-Driven Decision-Making: By integrating detailed category insights with the overall summary, organizations can make informed, data-driven decisions that align with sustainability objectives. For example, a high technology capability score may encourage investments in innovation.

Strategic Planning: The insights from the assessment guide organizations in developing actionable plans responsive to both internal strengths and external challenges. This ensures alignment with long-term business goals and enhances the organization's ability to adapt to market dynamics.

### *4.7. Limitations and Future Research Directions*

Despite its contributions, the study has some limitations:

Fixed Weights for Indicators: The use of fixed weights for various indicators might constrain the precision of the assessment. Future research could explore dynamic weighting systems to better capture the evolving nature of supply chain capabilities in Iran's energy sector.

Overall, this study underscores the importance of tailoring supply chain management strategies to the specific context of Iran's energy sector. By addressing the nuances and challenges unique to this sector, the recommendations provided can guide companies toward more effective and sustainable supply chain practices.

## **5. Conclusions**

Based on the modeling of the fuzzy expert system using sustainable supply chain capabilities, encompassing competitiveness, operational efficiency, technology, and resilience, the final system modeling has been achieved in this section. Therefore, taking into account the essential concepts, variables such as the competitiveness, operational efficiency, technology, and resilience capabilities of the sustainable supply chain were defined as input variables, while the level of sustainable supply chain capabilities was defined as the output variable. The design of the fuzzy expert system for sustainable supply chain capabilities is illustrated in Figure 9, with model outputs depicted in Figures 10–12. The Simulink tool was utilized for modeling and integrating fuzzy systems, as demonstrated in Figure 13.

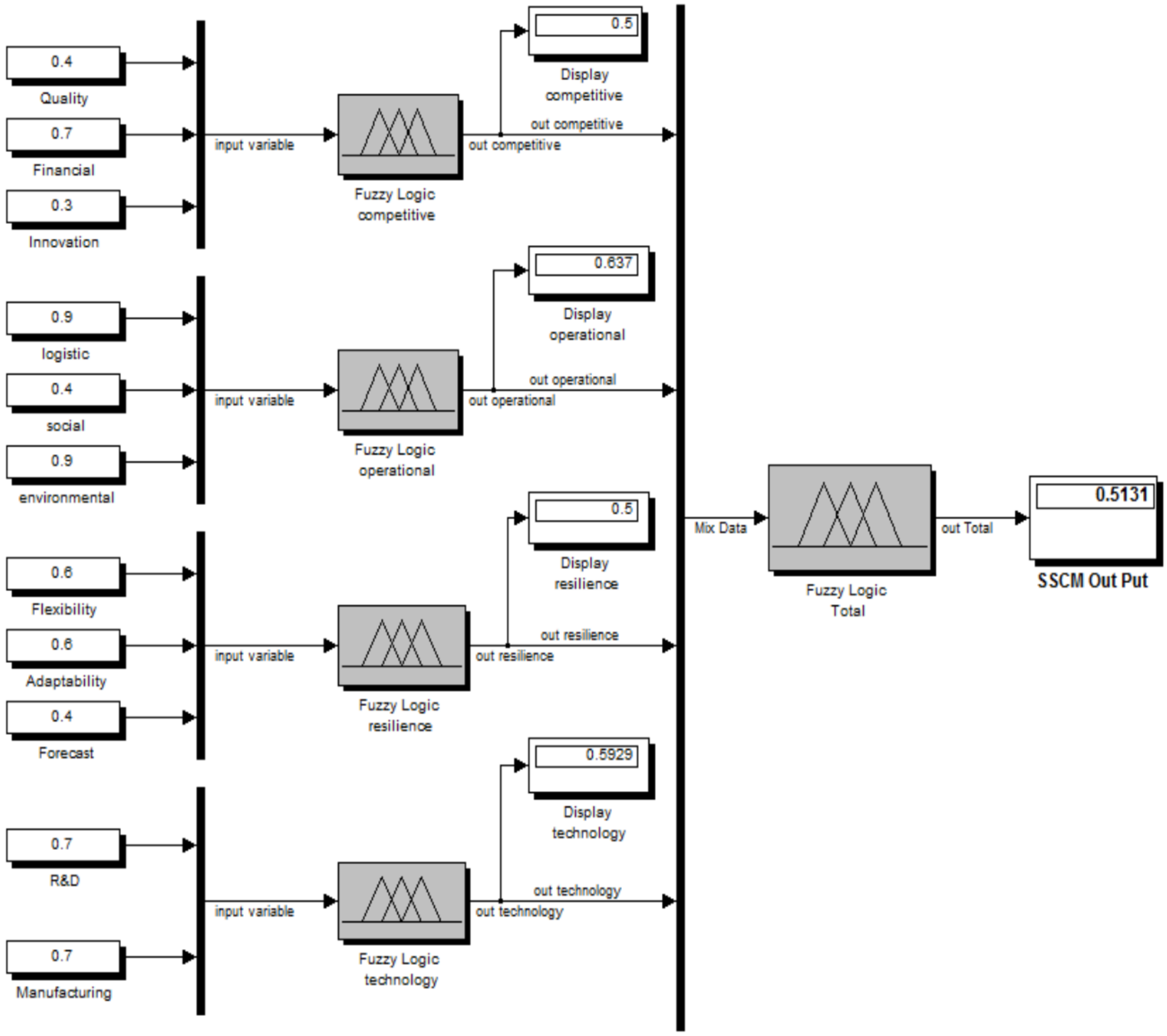


**Figure 13.** Simulink model design for sustainable supply chain capability.

**Assessment and Identification of Gaps:**

Energy companies in Iran should undertake a detailed audit of their current sustainable supply chain capabilities using the fuzzy expert system developed in this study. This audit should focus on evaluating key aspects such as competitiveness, operational efficiency, technological advancement, and resilience. Given the specific conditions of the Iranian energy sector, this audit will reveal performance gaps, such as deficiencies in technology integration or operational inefficiencies, that need targeted intervention. For instance, many Iranian energy companies face challenges related to outdated technology and infrastructure, which should be identified and prioritized for modernization.

**Technological Capability Enhancement:**

To advance technological capabilities, Iranian energy companies should carry out the following:

- Technology Transfer and Collaboration: To introduce cutting-edge technologies, establish alliances with global technology suppliers. This may entail entering into technology-sharing arrangements or joint enterprises. Working with European companies, for instance, might facilitate the integration of cutting-edge solar technology that conforms to global standards.

- Research and Development Investments: Invest funds in efforts for applied research and development that are specific to the demands of the Iranian energy industry. Creating R&D divisions and collaborating with nearby institutions helps stimulate technological innovation in sustainable energy. Local businesses' achievements in advancing their technology capacities through these kinds of partnerships can act as a template.
- Case Study Example: a well-known Iranian energy company collaborated with a European business to develop effective solar panels that increased market share and operational effectiveness.

**Operational Capability Improvement:**

To strengthen operational capabilities, companies should carry out the following:

- Enhance Logistics and Supply Chain Management: Use cutting-edge logistics solutions to streamline processes and cut expenses. Predictive analytics can reduce disruptions and increase efficiency in supply chain management, especially considering Iran's particular logistical problems.
- Social and Environmental Initiatives: Integrate social and environmental considerations into operational strategies. Emphasizing sustainable practices, such as reducing carbon emissions, is crucial for aligning with global standards and improving overall operational efficiency.
- Case Study Example: by implementing real-time logistics tracking technologies, an Iranian energy company enhanced its operations and significantly decreased delivery times and operating expenses.

**Resilience Capability Development:**

Companies should adopt flexible and adaptive strategies to enhance resilience, such as:

- Flexibility and Adaptability Programs: provide training courses that emphasize flexibility and scenario preparation in order to get ready for any unanticipated events that may affect Iran's energy industry.
- Environmental Analysis and Prediction Tools: to foresee and handle market shifts and environmental concerns, make investments in predictive analytics and environmental monitoring systems.
- Case Study Example: an Iranian company successfully implemented an environmental monitoring system that allowed for the proactive management of severe weather impacts, ensuring continuity in operations.

**Competitiveness Enhancement:**

To boost competitiveness, energy companies should carry out the following:

- Market Analysis and Strategy Development: Conduct thorough market analyses to identify emerging trends in the Iranian energy sector. Develop strategies that highlight product quality and sustainability.
- Product Quality Improvement: Invest in quality management systems to ensure that products meet high standards and differentiate from competitors. This is especially relevant for companies seeking to enter international markets.
- Case Study Example: An Iranian company achieved a competitive edge by obtaining ISO 14001 certification [40], which facilitated securing contracts with international clients prioritizing environmental sustainability.

**Collaborative Relationships with Academia and Research Centers:**

Establish long-term partnerships with universities and scientific research centers to leverage their expertise in sustainable supply chain management. This can include:

- Joint Research Projects: partner on research initiatives that focus on sustainable supply chain methodologies relevant to Iran's energy sector.

  - Consulting and Knowledge Exchange: engage academic experts to provide insights based on the latest research.
  - Case Study Example: an Iranian firm collaborated with a local university to develop energy-efficient technologies, leading to notable improvements in production efficiency.

These recommendations aim to strengthen the sustainable supply chain capabilities of Iranian energy companies, enhancing their resilience, competitiveness, and operational efficiencies in a complex and evolving global marketplace.

## 6. Future Research

In this study, four fundamental capabilities—competitiveness, operational efficiency, technology integration, and resilience—have been employed as input variables to model sustainable supply chain capabilities. It is recommended that future research expand upon this model by incorporating additional variables to enhance its complexity. Revisiting the modeling stages and comparing outcomes with those of this study would provide valuable insights into the evolving dynamics of sustainable supply chain management.

The utilization of triangular membership functions in the Delphi method for fuzzification in selecting decision-making variables underscores the current study's methodology. To enrich future investigations, exploring alternative membership functions beyond triangular ones is advised.

Similarly, the application of trapezoidal membership functions in expert system fuzzification for modeling the assessment of multiple capability levels in the sustainable supply chain highlights a specific approach. Future research should explore the efficacy of employing different membership functions to assess their impact on modeling accuracy and robustness.

In this study, all indicators within the studied groups were assigned fixed weights. For more precise evaluations in future research, employing a decision-making method to dynamically weight indicators and comparing it with fixed weighting approaches would yield deeper insights.

Additionally, while the weighting of all studied groups was uniformly fixed in this research, future endeavors could benefit from employing differentiated weights based on a decision-making method. Comparing outcomes between varied weighting methodologies and fixed approaches would provide a comprehensive understanding of their implications.

This study employed a fuzzy expert system for modeling purposes. It is recommended that future research compares this approach with alternative modeling methods to ascertain the optimal technique for modeling sustainable supply chains.

While conducted within the energy industry, extending this research to other industrial sectors and comparing findings would enhance its applicability and broaden the understanding of sustainable supply chain management across diverse domains. Such comparative studies would facilitate refining research outcomes and implications in various industrial contexts.

**Author Contributions:** Conceptualization, M.S.; Methodology, M.S. and K.Y.; Software, M.S. and K.Y.; Validation, M.S. and K.Y.; Formal analysis, M.S. and S.A.D.; Investigation, M.S. and K.Y. Resources, M.S. and S.A.D.; Data curation, K.Y.; Writing—original draft, M.S. and K.Y.; Writing—review and editing, S.A.D.; Supervision, M.S. and K.Y.; Project administration, K.Y.; Funding acquisition, S.A.D. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** This study, titled "A Comprehensive Evaluation Model for Sustainable Supply Chain Capabilities in the Energy Sector", was reviewed and approved by the Ethics Committee of FMTi (protocol code ED2024-0612657A, approved on 5 June 2024). This approval covers all relevant aspects of the study, including questionnaires and interviews conducted with participants.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Due to ongoing analysis and future work, the data are not publicly available but can be made available upon request to the corresponding authors.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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