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Blockchain Technology and Industry 5.0 synergy for sustainable development in RMG industries: an ISM and fuzzy DEMATEL approach

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Received: 22 August 2024 / Accepted: 21 November 2024
Published online: 04 December 2024

Abstract

This research explores the contribution of Blockchain Technology and Industry 5.0 in driving sustainability within Bangladeshi Ready-Made Garments (RMG) industry, with a focus on alignment with key Sustainable Development Goals (SDGs). The study employs Interpretive Structural Modeling (ISM) and fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods to identify and analyze 14 critical synergies that can drive sustainability. The ISM analysis categorizes the synergies into independent, dependent, and linkage variables, providing insights into their roles and significance within the system. Fuzzy DEMATEL further refines this understanding by evaluating the direct and indirect relationships among the linkage synergies. Key findings reveal the importance of synergies such as reverse logistics and recycling, supply chain collaboration & visibility and ethical practices in driving sustainability. This research contributes by offering a detailed analysis of how the synergy between Blockchain technology and Industry 5.0 can enhance sustainability practices in the RMG industry, providing actionable insights into the technological transformation of supply chain dynamics in support of global sustainability targets.

Keywords Blockchain Technology · Industry 5.0 · Sustainable development · RMG industry · Interpretive Structural Modeling · Fuzzy DEMATEL

1 Introduction

The Bangladeshi Ready-Made Garments (RMG) industry is a key driver of the nation's economy, standing as the largest exporter and employing millions of workers [1]. According to the BGMEA report (2020), the RMG sector accounts for over 80% of Bangladesh's total exports, highlighting significant contribution to the country's economic environment [2]. However, despite its economic significance, the industry faces significant disruptions and sustainability challenges. The production processes generate waste, pollution, and greenhouse gas emissions, which harm the environment. To secure long-term growth and sustainability, the RMG sector must adopt sustainable practices and integrate advanced technologies [3]. Industry 5.0, which integrates cutting-edge technology like blockchain and artificial intelligence (AI), has emerged as a disruptive force in the field of sustainable supply chain management (SSCM). These technologies play a pivotal role in continuously monitoring and managing manufacturing processes, supplementing conventional management techniques. Central to this transition is the development of reliable methods for recording, transmitting, and storing data, especially in sustainable supply chain (SSC) where diverse stakeholders collaborate [4]. On the other hand,

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Blockchain technology emerges as a promising solution, mitigating information asymmetry and transaction credibility issues through its decentralized, unnamable, traceable, collectively maintained, open, and transparent nature [5]. Defined as a decentralized database employing cryptographic methods for data block storage and management, Blockchain ensures transparency via consensus mechanisms, encryption algorithms, and distributed storage [6].

Blockchain Technology (BT) and Industry 5.0 (I5.0) are inextricably linked, complementing and strengthening the other's capabilities. Both concepts encourage decentralization and emphasize transparent and traceable processes [7]. Blockchain's distributed ledger technology is compatible with Industry 5.0's decision-making decentralization and enhanced collaboration between humans and robots [8]. Industry 5.0 automation ideas connect with blockchain smart contracts, enabling secure and automated agreements. The tamper-resistant features of Blockchain and Industry 5.0's focus on promoting trust in human–machine collaboration address security and trust, which are key to both technologies [9]. While they are not mutually exclusive, the incorporation of Blockchain significantly enhances the outcomes of Industry 5.0 activities, particularly in areas where transparency, security, and decentralized data management are critical.

The collaboration of BT with I5.0 in the Bangladeshi RMG industry represents a disruptive synergy aimed at attaining sustainable supply chain goals. The integration of Blockchain and Industry 5.0 solves the specific issues of the RMG industry in a sector critical to the country's economy. The distributed ledger of Blockchain ensures transparency and traceability, which is essential for tracing the clothing route from raw material source to distribution [10, 11]. When combined with the automation concepts of Industry 5.0, this transparency promotes effective resource usage and waste minimization, aligning with sustainability goals. The provenance tracking and smart contracts of BT encourage ethical sourcing and fair labor practices by confirming the legitimacy of resources and automating adherence to ethical labor standards [4]. Industry 5.0's collaborative approach promotes responsibility by empowering workers and enhancing human–machine collaboration. This is especially significant in the RMG industry, where human labor is essential. By allowing workers to engage in more creative and strategic tasks, Industry 5.0 reduces physical strain and boosts job satisfaction, leading to a more efficient and human-centered production environment [12]. Moreover, supply chain resilience is improved by Blockchain's decentralized structure, which is vital in an industry prone to disruptions. Manufacturers and suppliers are encouraged to use sustainable practices via tokenization incentives on the Blockchain [13, 14]. Furthermore, integration guarantees data security, which is important for environmental impact assessments and compliance procedures [9, 15].

Existing literature has predominantly focused on the individual impacts of BT and I5.0 on supply chains, emphasizing efficiency gains and technological advancements. However, the specific integration of these technologies and their combined impact on sustainability, especially in the context of RMG industries in Bangladesh, has been underexplored. The synergy of BT & I5.0 contributes significantly to sustainable supply chains. The features of Blockchain's such as transparency and traceability to enhance accountability in the supply chain, ensuring adherence to ethical and environmental standards [16]. Industry 5.0's focus on collaboration and adaptive processes promotes sustainable manufacturing practices and improved working conditions [17]. Together, these technologies create a supply chain that not only meets current sustainability goals but is also flexible and resilient to future challenges, aligning with the broader vision of global sustainability [9, 18]. Based on the gaps in previous studies, this study aims to address the following research question:

(a) What are the synergies and synergistic effects between BT and I5.0 in achieving sustainable development?
(b) What are the interrelations between these synergies?
(c) How can these synergies help effectively formulate strategic plans for sustainable development?

This research employed an integrated ISM and Fuzzy DEMATEL method to address the research questions. This integrated approach was chosen for several reasons. Firstly, ISM identifies the most significant relationships and driving forces within the system, providing a structured hierarchy. Subsequently, Fuzzy DEMATEL refines this detailed influence information by analyzing cause-and-effect relationships among the identified synergies. For the analysis of complex issues involving communicative and hierarchical structures, both ISM and Fuzzy DEMATEL work well [19]. Fuzzy DEMATEL uses a part-based perspective to identify direct and indirect links, whereas ISM uses a holistic approach to investigate complex systems [20]. The methodological process indicates that ISM can only handle binary options among variables, whereas Fuzzy DEMATEL has other options for capturing these relationships more comprehensively [21, 22]. Therefore, this study integrates ISM and Fuzzy DEMATEL to achieve more precise and insightful results, capitalizing on the strengths of both methods to analyze and interpret the complex interrelationships among the identified synergies in the RMG industry. The synergy of BT and I5.0 offers a customized solution that moves the Bangladeshi RMG sector closer to a transparent, ethically sound and sustainable supply chain environment. This study builds upon and extends prior research by providing a holistic understanding of the synergies inherent in the integration of BT and I5.0 for achieving SSC in the RMG sector which is pivotal for Bangladesh's economic landscape.

This paper is structured as follows: Sect. 2 provides an overview of existing research on Blockchain, Industry 5.0, and the identified research gaps. Section 3 explores the potential synergies between BT and I5.0 and their impact on sustainability. Section 4 describes research methodology. Section 5 presents numerical illustrations. Section 6 discusses the findings, interpretations, and alignment with sustainability goals. Finally, Sect. 7 summarizes key insights, managerial implications, and future research directions.

2 Literature review

In the dynamic landscape of Bangladesh's RMG industries, achieving sustainability in the SC is a pressing concern. The synergy between BT and I5.0 holds particular significance for RMG industries, as it addresses multifaceted challenges in the pursuit of a sustainable environment. Blockchain's transparent and secure ledger has the potential to transform the traceability of raw materials, guaranteeing ethical sourcing and adherence to sustainability standards [10, 11]. Concurrently, Industry 5.0's integration of advanced technologies fosters a collaborative and adaptive production environment, promoting efficiency and reducing environmental impact [8, 23]. The synergy between Blockchain and Industry 5.0 holds transformative potential for the RMG industry. Blockchain's capability to ensure transparency and traceability tackles issues related to ethical sourcing, while I5.0's focus on human–machine collaboration enhances manufacturing processes and working conditions [23]. This integrated approach fosters adaptive production, reducing waste and resource consumption. The study aims to demonstrate how this synergy can drive sustainable practices, establishing a supply chain ecosystem that is both technologically advanced and aligned with ethical and environmental standards.

Notably, recent studies have recognized the transformative potential of BT and I5.0 but often stopped short of delving into the nuances of their combined impact on sustainable supply chains [23]. This research aims to bridge this gap by elaborating on and synthesizing findings from these recent articles. In response to the growing interest in sustainable practices within the global supply chain, this study takes a focused approach to deciphering the synergies and challenges in integrating BT and I5.0. Kshetri et al. [24] identified a correlation between the use of Blockchain in SC activities and enhanced transparency. To estimate the impact of Blockchain adoption, the study considered a variety of characteristics such as cost, quality, speed, risk reduction, reliability, sustainability, and flexibility. Blockchain's role in SCM has been explored extensively, with studies highlighting its effectiveness in improving transparency, traceability, and efficiency [25]. The immutable nature of Blockchain ensures data integrity, crucial for SSC [26]. Additionally, Blockchain facilitates real-time tracking of products, enhancing the reliability of supply chain operations [27]. In the context of I5.0, significant impacts on manufacturing processes and the broader industry landscape are anticipated [28, 29]. Lu et al. [30] adopt a human-centric perspective, highlighting the significance of balancing automation and human involvement in I5.0 practices. The concept of I5.0 emphasizes human–machine collaboration, a shift from the automation-driven Industry 4.0. I5.0's emphasis on sustainability and customized manufacture is critical for modern SSC [31]. Furthermore, I5.0 incorporates advanced technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and robotics to build a resilient and adaptable supply chain environment [32]. The integration of Blockchain with SCM also offers solutions for reducing fraud, counterfeiting, and ensuring ethical sourcing [33]. Blockchain's potential in managing smart contracts and automating transactions is also significant [34]. The combination of BT and I5.0 technologies has been explored less but is gaining attention. Studies suggest that this synergy could lead to enhanced operational efficiencies and decision-making processes in SSC [35]. The use of BT within the I5.0 framework can further advance secure data sharing and collaborative innovation [36]. Despite the potential benefits, the adoption of the synergy between Blockchain and Industry 5.0 in SSC faces several challenges. Research identifies barriers such as technological complexity, lack of standardization, and regulatory uncertainty [24, 37].

In Industry 5.0, AI plays a crucial role, merging human expertise with advanced control and cognitive capabilities. Researchers like Verma et al. [9] describe I5.0 as a vision built on manufacturing principles, sophisticated control systems, and intelligent behavioral frameworks. A distinctive feature of I5.0 lies in synergy between humans and robots, with a particular emphasis on achieving mass customization. This collaborative framework is deeply intertwined with cyber-physical systems, fostering a visionary relationship between human operators and robotic counterparts. The emergence of collaborative robots forms the cornerstone of process management, representing a shift towards greener practices with a dedicated focus on sustainable production and development, as highlighted by Tanwar et al. [38] and Demir et al. [39]. The integration of smart contracts into I5.0 supply chains is crucial for ensuring effective security enforcement, access control, authentication, and service-oriented process automation. The use of smart contract-assisted digital identities becomes instrumental in effectively managing diverse assets, goods, items, and services. Notably, smart contracts efficiently interact with the underlying Blockchain network via a low-level interface, simplifying the process of stakeholder agreements. This automation, as highlighted by Jiang et al. [40], contributes to the overall efficiency enhancement within SSC. Existing privacy and security solutions, while noteworthy, are deemed insufficient, particularly in addressing the anomalous behavior of sensor nodes. The establishment of trust in data sharing and control emerges as a critical consideration, especially in the context of heterogeneous and autonomous networks collaborating within the framework of I5.0. To tackle this challenge, Blockchain emerges as a promising solution, providing transparent ledgers that effectively manage and control industrial process data, as emphasized by Verma et al. [9].

The study highlights a critical gap in the literature by highlighting the necessity of a thorough examination of the synergies between BT & I5.0 that is especially designed for Bangladeshi RMG industry. The motivation stems from the urgency to address sustainability challenges unique to this industry, aligning with global expectations and ensuring long-term viability. Looking ahead, the integration of AI, BT and the IoT is set to customize service offerings for users, aligning with the I5.0 vision of mass personalization. The envisioned Industry 5.0 landscape integrates human influence into automation processes, harnessing precise and accurate control and modeling systems. In the transition to digitization and smart industries, the heterogeneous flow of data across business processes raises concerns about system privacy vulnerabilities. Security and privacy emerge as paramount concerns before the seamless provision of services, as articulated by Verma et al. [9]. The accumulation and processing of data during Industry 5.0 processes pose potential privacy challenges, necessitating robust privacy preservation measures. Additionally, workforce training becomes crucial to align human resources with machine intelligence, ensuring a seamless integration with robots to scale up manufacturing processes in the industry. In addressing these challenges, Blockchain emerges as a pivotal solution within the I5.0 framework, offering trusted control through auditable, chronological, and timestamped ledgers. By bridging this research gap, the study endeavors to furnish actionable insights, strategic frameworks, and guidelines for stakeholders in the RMG sector. The overarching goal is to cultivate an environment conducive to sustainable and resilient SC practices through the synergistic integration of BT and I5.0.

3 Synergy between BT and I5.0

The concept of synergy in this study refers to the collaborative effect of integrating BT and I5.0 to create transformative changes in the Bangladeshi RMG supply chains. These synergies are vital for sustainability as they help to streamline processes, enhance visibility across the supply chain, and facilitate ethical practices. For instance, the synergy between BT's decentralized ledger and I5.0's AI-driven automation can significantly reduce inefficiencies, track environmental impact in real-time, and ensure compliance with sustainability standards. Such interactions between BT and I5.0 not only improve supply chain transparency but also foster responsible sourcing, energy efficiency, and waste reduction, ultimately contributing to the sustainability goals of the RMG sector. The following Table 1 represents synergies between BT and I5.0 for SSCM.

The synergies between BT and I5.0 offer promising avenues for advancing sustainability in supply chains. By synergizing BT and I5.0, industries can enhance *energy efficiency and sustainability* through real-time monitoring and optimization of energy consumption [41]. Additionally, the tamper-proof recordkeeping enabled by Blockchain can revolutionize *eco-friendly product lifecycle management*, empowering companies to make informed decisions at every stage [42, 43]. *Supply chain collaboration and visibility* are heightened, fostering transparency and effective resource allocation [44]. *Real-time environmental impact monitoring* becomes achievable, enabling proactive measures to minimize ecological footprints [45]. Furthermore, the integration allows for the creation of *decentralized renewable energy platforms*, promoting sustainable energy usage in smart manufacturing [46]. These synergies collectively drive sustainable practices, laying the foundation for greener and more resilient supply chains.

By leveraging Industry 5.0's adaptive manufacturing capabilities and Blockchain's traceability features, *circular economy principles* can be effectively implemented. This synergy enables the tracking, verification, and potential recycling or repurposing of products and materials, thereby reducing waste and promoting resource efficiency [47]. Moreover, the integration facilitates *dynamic inventory management*, leading to better demand forecasting and waste reduction [48]. Additionally, *smart warehousing* concepts, enhanced by Blockchain's transparency, optimize inventory management and distribution processes, further minimizing resource usage [49]. Furthermore, the collaboration supports efficient *reverse logistics and recycling* efforts, contributing to a more sustainable and circular

Table 1 Synergy between BT & I5.0

Sl. No	Name of the Synergy	References
Synergy-1	Energy Efficiency & Sustainability	[41]
Synergy-2	Eco-Friendly Product Lifecycle Management	[42, 43]
Synergy-3	Supply Chain Collaboration & Visibility	[44]
Synergy-4	Real-Time Environmental Impact Monitoring	[45]
Synergy-5	Decentralized Renewable Energy Platforms	[46]
Synergy-6	Circular Economy Implementation	[47]
Synergy-7	Dynamic Inventory Management	[48]
Synergy-8	Smart Warehousing & Distribution	[49]
Synergy-9	Reverse Logistics & Recycling	[33]
Synergy-10	Smart Contracts for Sustainable Agreements	[50]
Synergy-11	Ethical & Fair-Trade Practices	[51]
Synergy-12	Responsible Sourcing & Procurement	[52]
Synergy-13	Emission Tracking & Carbon Footprint Reduction	[53]
Synergy-14	Automated Quality Control for Sustainability Standards	[54]
Synergy-15	Automated Compliance & Reporting	[55]
Synergy-16	Eco-Friendly Packaging and waste reduction	[56]
Synergy-17	Community & Social Impact Monitoring	[18]
Synergy-18	Blockchain-Based Green Certifications	[57, 58]
Synergy-19	Digital Twin Technology for Sustainability Simulation	[59]
Synergy-20	Sustainable Finance & Investment	[60]

supply chain [33]. Lastly, the use of smart contracts on the Blockchain automates and enforces *sustainable agreements*, ensuring adherence to *fair labor practices*, ethical sourcing, and environmental standards [50, 51].

Responsible sourcing and procurement can be ensured through the utilization of blockchain technology, which verifies the authenticity and ethical sourcing of raw materials, providing transparent information to consumers about the origins of products [52]. Furthermore, combining Industry 5.0's real-time monitoring with Blockchain's transparency facilitates accurate *tracking of emissions* throughout the supply chain, leading to reduced carbon footprints by identifying areas for improvement in energy consumption and transportation [53]. Additionally, Industry 5.0's focus on automation in manufacturing processes, coupled with Blockchain's traceability, enables the implementation of *automated quality control systems* to ensure products meet sustainability standards, thereby minimizing defects and waste [54]. Moreover, the synergy between Industry 5.0's automation capabilities and Blockchain's data integrity ensures streamlined compliance processes, automating verification of adherence to sustainability standards and enabling *real-time reporting* to reduce administrative burdens while ensuring a more sustainable supply chain [55]. Finally, Blockchain can be used to verify the authenticity of *eco-friendly packaging materials*, complementing Industry 5.0's smart manufacturing processes to optimize packaging designs and reduce waste, thereby promoting sustainability [56].

Blockchain technology, with its transparent and decentralized nature, offers a robust solution for monitoring the *social impact* of supply chain activities, ensuring fair wages, evaluating social responsibility initiatives, and overseeing community development projects [18]. This aligns with sustainable and ethical business practices, ensuring that supply chain activities positively contribute to social welfare. Additionally, establishing *blockchain-based green certifications* for products enhances transparency and credibility in sustainability standards adherence, fostering trust among consumers and stakeholders while promoting environmentally conscious consumption habits [57, 58]. Furthermore, combining Industry 5.0's *digital twin concept* with Blockchain empowers organizations to conduct sustainability simulations, enabling informed decisions that minimize environmental impact and drive sustainable practices [59]. Lastly, blockchain technology facilitates transparent financial transactions aligned with environmental, social, and governance (ESG) principles, enabling *sustainable finance and investment* directing capital towards positive environmental and social change [60].

4 Research methodology

4.1 Data collection

For this study, we focused on the small and medium sized RMG industries in Dhaka, Bangladesh, to collect data necessary for identifying and analyzing synergies. Our data collection process involved multiple steps to ensure comprehensive and robust insights. Initially, a thorough literature review was conducted to identify potential synergies. This review identified 20 synergies, which were then discussed with a panel of 10 experts. Based on their feedback, we refined and reduced the list to 14 key synergies for subsequent analysis. The excluded 6 synergies might have overlapping benefits with other synergies or those that may not be as critical or impactful in the specific context of the Bangladeshi RMG industry. Based on expert feedback, the refined list of synergies includes Energy Efficiency & Sustainability (S1), Eco-Friendly Product Lifecycle Management (S2), Supply Chain Collaboration & Visibility (S3), Real-Time Environmental Impact Monitoring (S4), Decentralized Renewable Energy Platforms (S5), Circular Economy Implementation (S6), Dynamic Inventory Management (S7), Reverse Logistics & Recycling (S8), Ethical & Fair-Trade Practices (S9), Responsible Sourcing & Procurement (S10), Emission Tracking & Carbon Footprint Reduction (S11), Automated Compliance & Reporting (S12), Eco-Friendly Packaging and Waste Reduction (S13), and Digital Twin Technology for Sustainability Simulation (S14).

This research selects experts for the focus group discussion and survey based on their extensive experience and expertise in the RMG sector, particularly in areas related to Blockchain Technology, Industry 5.0, and sustainability. The criteria for selecting these experts included (i) a minimum of 5 years of professional experience in RMG supply chain management or related fields, (ii) active involvement in sustainability initiatives or Industry 4.0/5.0 practices, and (iii) academic experts with research publications on sustainable supply chains or emerging technologies in manufacturing. This blend of practical and theoretical perspectives ensured a comprehensive evaluation of synergies, which contributed significantly to the study's validity. We invited 15 experts to participate in a focus group discussion, during which the ISM method was applied to structure and prioritize the synergies effectively. For the Fuzzy DEMATEL method, questionnaires were distributed to 30 experts, with 22 responses received (10 academic experts and 12 professionals). This diverse group of experts evaluated the synergies from multiple perspectives: managerial, informational, integrational, production, and environmental, providing a balanced and robust foundation for analyzing synergies impacting the RMG industry.

4.2 Reliability, validity, and consistency analysis

Before focusing on the ISM and fuzzy DEMATEL analysis, it is essential to establish the reliability, validity, and consistency of the data. This step is crucial to ensure that the data is robust and suitable for further analysis. The study involved a sample size of 22 respondents, utilizing a five-point linguistic scale to collect data, which allowed for a range of responses from "No Influence" to "Very High Influence." Data analysis was conducted using SPSS 22 software, chosen for its robust statistical capabilities.

To assess the reliability of the data, Cronbach's alpha was calculated, yielding a value of 0.927. This value, falling within the recommended range of 0.70 to 0.95, indicates a high level of internal consistency among the items used in the scale, suggesting that the data is reliable. Validity was evaluated using the KMO measure, which resulted in a value of 0.638. A KMO value above 0.60 is considered adequate for factor analysis, confirming that the sample size is sufficient and appropriate for the research. Consistency was measured using the Kappa statistic, which resulted in a value of 0.213. A Kappa value in this range (0.21–0.40) signifies a fair degree of consistency, indicating that there is a reasonable level of agreement among the respondents' answers, which justifies further analysis (see Appendix Tables 9, 10).

4.3 Proposed methods

The reliability, validity, and consistency analysis results confirm that the data is suitable for subsequent ISM and Fuzzy DEMATEL analysis. The ISM approach is used to analyze the impact of each factor on one another and develop an interconnectivity model. ISM excels in systematically utilizing conceptual, judgmental, and computational resources to understand the contextual relations among complex system elements, making it ideal for examining intricate, real-world situations with non-linear interconnections [61]. It interprets contextual relationships among pairs of elements, utilizing qualitative data collection methods like in-depth interviews or group discussion to capture experts' collective opinions and knowledge [62]. ISM and MICMAC analysis are complementary methods used to analyze complex systems and their interrelationships. While ISM structures these systems hierarchically by identifying direct relationships among factors, MICMAC analysis further categorizes these factors based on their driving power and dependence. Together, ISM and MICMAC provide a comprehensive framework for understanding and analyzing the dynamics of influence and dependence within complex systems [63].

The fuzzy DEMATEL method is employed to evaluate interdependencies and impacts among variables under uncertain conditions, particularly in maintaining supply chain sustainability. This approach offers valuable insights into the complex relationships within sustainable supply chains by considering both the direct and indirect effects of various factors. It aids in identifying key drivers and facilitates effective decision-making to enhance overall supply chain performance [64–67]. The choice of the fuzzy DEMATEL method is motivated by the need to address the inherent uncertainties and complexities in the relationships among identified factors, barriers, and synergies [68, 69]. Traditional methods may be inadequate in BT and I5.0 synergy, where dynamics are multifaceted and not strictly deterministic. The fuzzy DEMATEL method excels in managing imprecise and uncertain information, providing a nuanced understanding of the interdependencies between factors, barriers, and synergies [64, 70].

Previous studies have utilized various Multi-Criteria Decision-Making methods in sustainable supply chain research to identify, prioritize, and analyze the interrelations among factors and barriers that impact the achievement of sustainable supply chain goals [71, 72]. Compared to fuzzy ISM and TISM (Total Interpretive Structural Modeling), the ISM method was chosen for the following reasons: (i) while fuzzy ISM enhances precision by incorporating uncertainty and ambiguity from expert opinions, ISM offers the necessary clarity to establish a hierarchical structure of synergies without adding unnecessary complexity [73]; (ii) although TISM improves the interpretive dimension, it can introduce greater subjectivity [36]. To overcome the limitations of ISM, we integrated Fuzzy DEMATEL, which enables the evaluation of relationship strengths and indirect effects, achieving a balanced approach between simplicity and analytical depth. The fuzzy DEMATEL method, as recommended by Uygun and Dede [74], is a robust approach for evaluating factors and identifying causal relationships among them. However, ISM is regarded as the most suitable method for establishing hierarchical levels and inter-relationships among these synergies. The fuzzy DEMATEL approach also categorizes synergies into causes and effects [19, 20]. Given these characteristics, the integrated ISM and fuzzy DEMATEL method has been selected to assess synergies and elucidate their causal relationships in pursuit of sustainable development goals.

The step-by-step procedures of the research methodologies are outlined in Sects. 4.3.1 and 4.3.2. These methodologies are briefly described, focusing on essential principles and equations, as these are well-known and well-established techniques. Only the necessary details are highlighted to avoid unnecessary elaboration.

4.3.1 Interpretive structural modeling approach

Steps to Develop an ISM Model are the followings:

Step 1: Identify Synergies between BT & I5.0

Step 2: Develop the SSIM

Create an SSIM to capture the pairwise relationships among the synergies. This involves experts deciding on the type of relationship between each pair of synergies:

- V: Synergy i influences Synergy j
- A: Synergy j influences synergy i
- X: Synergies i and j influence each other
- O: No relationship between Synergies i and j

Step 3: Develop the initial reachability matrix

Convert the SSIM to an initial reachability matrix using the following rules:

- V: 1 for (i, j) and 0 for (j, i)
- A: 0 for (i, j) and 1 for (j, i)
- X: 1 for both (i, j) and (j, i)
- O: 0 for both (i, j) and (j, i)

Step 4: Develop the final reachability matrix

Incorporate transitivity into the initial reachability matrix.

Step 5: Level Partitioning

For level partitioning, we need to identify the reachability, antecedent, and intersection sets for each synergy.

- Reachability Set (R(i)): The set of synergies that can be reached from synergy iii.
- Antecedent Set (A(i)): The set of synergies that can reach synergy iii.
- Intersection Set (R(i) ∩ A(i)): The common elements in the reachability and antecedent sets for synergy iii.

Step 6: Developing an ISM Model

Step 7: MICMAC Analysis

4.3.2 Fuzzy DEMTEL method

The Steps of the Fuzzy DEMATEL Method are given in the followings:

Step 1: Generate the fuzzy direct- relation matrix

To model the relationships among the n synergies, the first step is to create an $n \times n$ matrix. Each element in this matrix represents the influence of the synergy in each row on the synergy in each column and is expressed as a fuzzy number. The fuzzy direct-relation matrix, denoted as Z, is generated by calculating the arithmetic mean of all expert opinions.

$$z = \begin{bmatrix} 0 & \cdots & \tilde{z}_{n1} \\ \vdots & \ddots & \vdots \\ \tilde{z}_{1n} & \cdots & 0 \end{bmatrix} \tag{1}$$

Step 2: Normalize the fuzzy direct-relation matrix

$$\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right) \tag{2}$$

where,

$$r = \max_{i,j}\left\{\max_i \sum_{j=1}^{n} u_{ij}, \max_j \sum_{i=1}^{n} u_{ij}\right\} \quad i,j \in \{1,2,3,\dots,n\}$$

Step 3: Calculate the fuzzy total-relation matrix

$$\tilde{T} = \lim_{k\to+\infty}\left(\tilde{x}^1 \oplus \tilde{x}^2 \oplus \cdots \oplus \tilde{x}^k\right) \tag{3}$$

Step 4: Defuzzify into crisp values

To obtain crisp values from the total-relation matrix, the CFCS (Centroid of Fuzzy Composite Scores) method is employed. The CFCS method involves the following steps:

$$\begin{aligned} l_{ij}^{n} &= \frac{\left(l_{ij}^{t} - \min l_{ij}^{t}\right)}{\Delta_{min}^{max}} \\ m_{ij}^{n} &= \frac{(m_{ij}^{t} - min l_{ij}^{t})}{\Delta_{min}^{max}} \\ u_{ij}^{n} &= \frac{(u_{ij}^{t} - min l_{ij}^{t})}{\Delta_{min}^{max}} \end{aligned} \tag{4}$$

So that,

$$\Delta_{min}^{max} = \max u_{ij}^{t} - \min l_{ij}^{t} \tag{5}$$

Calculating the upper and lower bounds of normalized values:

$$l_{ij}^{s} = m_{ij}^{n} \Big/ \left(1 + m_{ij}^{n} - l_{ij}^{n}\right)$$
$$u_{ij}^{s} = u_{ij}^{n} \Big/ \left(1 + u_{ij}^{n} - l_{ij}^{n}\right) \tag{6}$$

Calculating total normalized crisp values:

$$x_{ij} = \frac{[l_{ij}^{s}\left(1 - l_{ij}^{s}\right) + u_{ij}^{s} \times u_{ij}^{s}]}{[1 - l_{ij}^{s} + u_{ij}^{s}]} \tag{7}$$

Step 5: Set the Threshold Value

To compute the internal relations matrix, a threshold value must be determined. This is done by calculating the average of the values in matrix T. Once the threshold intensity is defined, all values in matrix T that fall below this threshold are set to zero, ensuring that only significant relations are considered for further analysis.

Step 6: Final Output and Causal Relation Diagram

In this step, the sum of each row and each column in matrix T is calculated. From these sums, two key metrics are derived: D + R and D – R. D + R indicates the overall importance of factor *i* within the system, while D – R represents the net influence of factor *i* on the system. The row sums (D) and column sums (R) are determined accordingly.

$$D = \sum_{j=1}^{n} T_{ij}$$
$$R = \sum_{i=1}^{n} T_{ij} \tag{8}$$

5 Numerical illustrations

5.1 Application ISM method

In this section, this research presents the application of the ISM methodology to analyze the 14 critical synergies identified between BT and I5.0. The process begins with the Structural Self-Interaction Matrix, derived from focused group discussions, as shown in Table 2. The final reachability matrix is presented in Table 3, with Table 4 illustrating the level partitioning of these synergies. Additional details can be found in Appendix Tables 11, 12, 13.

5.2 Application of fuzzy DEMATEL method

Following the ISM analysis, our research moves to the Fuzzy DEMATEL analysis. The ISM findings indicate that Circular Economy Implementation (S6) and Eco-Friendly Packaging and Waste Reduction (S13) are dependent synergies with low driving power. Conversely, Dynamic Inventory Management (S7) and Digital Twin Technology for Sustainability Simulation (S14) are identified as independent synergies with low dependence power. The linkage synergies, including S1, S2, S3, S4, S5, S8, S9, S10, S11, and S12, exhibit bidirectional influence, highlighting their strong driving and dependence power. Consequently, our Fuzzy DEMATEL analysis focuses exclusively on these linkage synergies to thoroughly examine their interrelations and influence within the system, providing a comprehensive understanding of their roles in achieving sustainable development in the Bangladeshi RMG industry.

The following Table 5 presents the direct relation matrix, while Table 6 outlines the fuzzy scale. Subsequently, Table 7 provides the fuzzy total-relation matrix. For additional details see Appendix Tables 14, 15.

In this study, a threshold value of 0.177 is set. Any causal relations with values below this threshold are disregarded and assigned a value of zero. The final results, reflecting the corresponding causal relationships, are shown in Table 8.

Table 2 Structural self-interaction matrix (SSIM)

Variables	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
S1		O	V	A	X	O	O	V	V	V	V	V	V	A
S2			A	O	A	O	O	V	A	O	O	O	V	A
S3				X	A	O	O	V	X	X	V	A	V	O
S4					O	O	O	V	A	O	X	V	V	O
S5						O	O	V	O	O	V	O	O	A
S6							O	A	A	A	O	O	X	O
S7								O	O	O	O	V	O	O
S8									X	V	O	O	V	O
S9										X	V	A	O	O
S10											O	A	O	O
S11												X	O	O
S12													O	O
S13														O
S14														

Table 3 Final reachability matrix (FRM)

Variables	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	Driving power
S1	1	1*	1	1*	1	1*	0	1	1	1	1	1	1	0	12
S2	1*	1	1*	1*	1*	1*	0	1	1*	1*	1*	1*	1	0	12
S3	1*	1	1	1	1*	1*	0	1	1	1	1	1*	1	0	12
S4	1	1*	1	1	1*	1*	0	1	1*	1*	1	1	1	0	12
S5	1	1	1	1*	1	1*	0	1	1*	1*	1	1*	1*	0	12
S6	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2
S7	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1	1*	0	13
S8	1*	1*	1*	1*	1*	1	0	1	1	1	1*	1*	1	0	12
S9	1*	1	1	1	1*	1	0	1	1	1	1	1*	1*	0	12
S10	1*	1*	1	1*	1*	1	0	1*	1	1	1*	1*	1*	0	12
S11	1*	1*	1*	1	1*	1*	0	1*	1*	1*	1	1	1*	0	12
S12	1*	1*	1	1*	1*	1*	0	1*	1	1	1	1	1*	0	12
S13	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2
S14	1	1	1*	1*	1	1*	0	1*	1*	1*	1*	1*	1*	1	13
Dependence Power	12	12	12	12	12	14	1	12	12	12	12	12	14	1	

6 Result and discussion

6.1 ISM-based model: key observations and interpretation

The ISM-based model (as shown in Fig. 1) provides a structured framework for understanding the hierarchical relationships and interdependencies among various synergies critical to achieving sustainability in the RMG industry. This model categorizes the factors into three levels, each with distinct characteristics and roles within the system. This structured approach helps to identify key drivers, linkages, and dependent variables essential for strategic decision-making in the RMG industry.

6.1.1 Level I (dependent synergies)

The synergies at this level are highly dependent on the success of other initiatives. They rely on the successful implementation of other synergies to achieve their objectives. These synergies, Circular Economy Implementation (S6) and

Table 4 Level partitioning (LP)

Elements	Reachability set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi) ∩ A(Ni)	Level
S1	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S2	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S3	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S4	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S5	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S6	6, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14,	6, 13,	1
S7	7,	7,	7,	3
S8	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S9	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S10	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S11	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S12	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 14,	1, 2, 3, 4, 5, 8, 9, 10, 11, 12,	2
S13	6, 13,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14,	6, 13,	1
S14	14,	14,	14,	3

Eco-Friendly Packaging and Waste Reduction (S13), highlight areas that require robust support from other initiatives. Their lack of direct and transitive links signifies their dependence on the broader system's effectiveness. For these variables to succeed, foundational and interlinked strategies must be implemented to support their development and impact.

6.1.2 Level II (linkage synergies)

These synergies form the core of the system, characterized by their bidirectional influence. They are both influenced by and exert influence over other variables, making them essential for maintaining balance and coherence within the system. Their interconnected nature makes them central to the system's functionality and effectiveness. For instance, Supply Chain Collaboration & Visibility (S3) and Emission Tracking & Carbon Footprint Reduction (S11) are integral to ensuring a comprehensive and integrated approach to sustainability within the RMG industry.

- Interconnectedness: The linkage variables exhibit a high degree of interconnectedness. For instance, S1 has direct links with S3, S5, S8, S9, S10, S11, S12, S13, and transitive links with S2, S4, S6, highlighting its central role in the system.
- Bidirectional Influence: These variables both influence and are influenced by others, making them pivotal for system coherence. For example, S2 impacts S1, S3, S4, S5, S6, S9, S10, S11, S12 directly and indirectly impacts others, indicating its significant role.

The extensive interconnections among these variables underscore the necessity of maintaining a well-coordinated and interdependent system where multiple factors work in tandem. For instance:

- Energy Efficiency & Sustainability (S1) impact numerous other variables directly, indicating its pivotal role in the system.
- Supply Chain Collaboration & Visibility (S3) and Ethical & Fair-Trade Practices (S9) exhibit multiple direct and indirect links, highlighting their importance in fostering an integrated approach to sustainability.
- The interdependencies among these variables mean that improvements in one area can lead to positive cascading effects throughout the system. Policies and initiatives targeting these variables are likely to yield widespread benefits across the system.

6.1.3 Level III (independent synergies)

Independent variables like Dynamic Inventory Management (S7) and Digital Twin Technology for Sustainability Simulation (S14) act as the main drivers for systemic change. These synergies have multiple direct and transitive links, indicating their

Table 5 The direct relation matrix

	S1	S2	S3	S4	S5	S8	S9	S10	S11	S12
S1	(0.000,0.000,0.000)	(0.125,0.250,0.500)	(0.250,0.500,0.750)	(0.000,0.000,0.250)	(0.750,1.000,1.000)	(0.000,0.000,0.250)	(0.000,0.000,0.250)	(0.000,0.000,0.250)	(0.250,0.500,0.750)	(0.000,0.000,0.250)
S2	(0.000,0.250,0.500)	(0.000,0.000,0.000)	(0.250,0.500,0.750)	(0.250,0.500,0.750)	(0.125,0.250,0.500)	(0.500,0.750,1.000)	(0.125,0.250,0.500)	(0.125,0.375,0.625)	(0.125,0.375,0.625)	(0.000,0.250,0.500)
S3	(0.000,0.250,0.500)	(0.250,0.500,0.750)	(0.000,0.000,0.000)	(0.625,0.875,1.000)	(0.250,0.500,0.750)	(0.375,0.625,0.875)	(0.500,0.750,0.875)	(0.375,0.625,0.750)	(0.375,0.625,0.875)	(0.250,0.500,0.750)
S4	(0.250,0.500,0.750)	(0.500,0.750,1.000)	(0.375,0.625,0.875)	(0.000,0.000,0.000)	(0.000,0.125,0.375)	(0.375,0.625,0.875)	(0.250,0.500,0.750)	(0.125,0.375,0.625)	(0.750,1.000,1.000)	(0.250,0.500,0.750)
S5	(0.750,1.000,1.000)	(0.250,0.500,0.750)	(0.000,0.250,0.500)	(0.250,0.500,0.750)	(0.000,0.000,0.000)	(0.375,0.625,0.875)	(0.000,0.000,0.250)	(0.000,0.250,0.500)	(0.375,0.625,0.875)	(0.000,0.250,0.500)
S8	(0.250,0.500,0.750)	(0.500,0.750,1.000)	(0.250,0.500,0.750)	(0.250,0.500,0.750)	(0.000,0.250,0.500)	(0.000,0.000,0.000)	(0.375,0.625,0.750)	(0.375,0.625,0.875)	(0.250,0.500,0.750)	(0.125,0.375,0.625)
S9	(0.250,0.500,0.750)	(0.000,0.250,0.500)	(0.500,0.750,1.000)	(0.500,0.750,1.000)	(0.000,0.250,0.500)	(0.250,0.500,0.750)	(0.000,0.000,0.000)	(0.625,0.875,1.000)	(0.375,0.625,0.875)	(0.250,0.500,0.750)
S10	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.250,0.500,0.750)	(0.250,0.500,0.750)	(0.500,0.750,1.000)	(0.000,0.000,0.000)	(0.125,0.250,0.500)	(0.250,0.500,0.750)
S11	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.000,0.000,0.250)	(0.250,0.500,0.750)	(0.000,0.250,0.500)	(0.500,0.750,1.000)	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.000,0.000,0.000)	(0.375,0.625,0.750)
S12	(0.250,0.500,0.750)	(0.250,0.500,0.750)	(0.250,0.500,0.750)	(0.000,0.250,0.500)	(0.000,0.000,0.250)	(0.000,0.250,0.500)	(0.500,0.750,1.000)	(0.250,0.500,0.750)	(0.500,0.750,1.000)	(0.000,0.000,0.000)

Table 6 Fuzzy scale

Code	Linguistic terms	L	M	U
1	No influence	0	0	0.25
2	Very low influence	0	0.25	0.5
3	Low influence	0.25	0.5	0.75
4	High influence	0.5	0.75	1
5	Very high influence	0.75	1	1

potential to drive systemic improvements and set the stage for achieving long-term sustainability goals. S7 has direct links with S1, S2, S5 and transitive links with other factors, suggesting its foundational role in inventory management. Similarly, S14's direct link with S12 and multiple transitive links highlight its potential to drive sustainability through digital twin technology. They exert influence over other synergies but are less affected by them, making them crucial initiators of change and innovation. Their strong influence and foundational roles emphasize the importance of having robust initiatives that can instigate necessary changes and innovations.

The ISM-based model presented in Fig. 1 provides key insights into the hierarchical structure of synergies within the RMG supply chain management. It reveals a clear hierarchy, where dependent synergies rely on the success of those positioned at higher levels. The model highlights the intricate interdependencies among middle-layer synergies, emphasizing the importance of a holistic approach to sustainability. Additionally, identifying independent synergies offers strategic leverage points for initiating system-wide positive change. Overall, the ISM model serves as a valuable framework for understanding the dynamics within the RMG supply chain management, helping organizations make informed decisions by supporting dependent synergies, capitalizing on independent drivers, and managing interconnections effectively. This approach fosters the successful implementation of sustainability initiatives, driving progress toward long-term sustainability goals.

6.2 MICMAC analysis: key observations and interpretation

The MICMAC analysis of the synergies within the RMG industry reveals significant insights into the interrelationships and influences of various synergies based on their dependence and driving power. The MICMAC analysis (as shown in Fig. 2) highlights the interconnected nature of synergies within the RMG industry, with an emphasis on the importance of linkage synergies. The absence of autonomous variables suggests that every synergy considered in this study plays a vital role in the system's overall functionality and sustainability. The identification of dependent variables such as circular economy implementation and eco-friendly packaging emphasizes the need for a supportive and conducive environment, driven by other critical synergies, to achieve success in these areas.

The dominance of linkage synergies underscores the complexity and interdependence of sustainable practices in the RMG industry. These synergies are crucial levers for change, where strategic improvements can cascade through the entire system, enhancing overall performance and sustainability. Consequently, focusing on optimizing these linkage synergies can yield significant benefits. Lastly, the independent synergies identified, namely dynamic inventory management and digital twin technology, are strategic drivers of change. Their high driving power indicates that they can lead to substantial advancements in operational efficiency and sustainability, serving as key areas for investment and development.

6.3 Fuzzy DEMATEL analysis: key observations and interpretation

The Fuzzy DEMATEL analysis provides an in-depth understanding of the synergies within the RMG industry, highlighting the importance and influence of various factors in the system. The key findings from the analysis reveal that Reverse Logistics & Recycling (S8) is ranked the highest in importance with a D + R value of 4.061 and a D-R value of − 0.043, indicating its crucial role in managing waste and promoting recycling processes. This suggests a strong need for effective waste management practices to reduce environmental impacts and enhance sustainability in the RMG industry. Supply Chain Collaboration & Visibility (S3) is ranked second in importance with a D + R value of 3.983 and a D − R value of 0.449, emphasizing the necessity of enhancing collaboration and visibility across the supply chain for efficient operations and better environmental management. Ethical & Fair-Trade Practices (S9), with a D + R value of 3.892 and a D-R value of 0.391, highlight the importance of maintaining the industry's reputation and ensuring fair treatment of workers. Adopting these practices enhances the industry's sustainability and social responsibility, contributing to a positive global image.

Table 7 The fuzzy total-relation matrix

	S1	S2	S3	S4	S5	S8	S9	S10	S11	S12
S1	(0.012,0.044,0.292)	(0.024,0.067,0.345)	(0.037,0.096,0.386)	(0.010,0.043,0.332)	(0.107,0.162,0.379)	(0.013,0.050,0.371)	(0.005,0.030,0.316)	(0.004,0.030,0.305)	(0.045,0.114,0.442)	(0.004,0.034,0.311)
S2	(0.008,0.094,0.461)	(0.011,0.058,0.387)	(0.042,0.125,0.499)	(0.045,0.127,0.497)	(0.021,0.081,0.409)	(0.079,0.169,0.579)	(0.028,0.098,0.460)	(0.027,0.107,0.457)	(0.031,0.130,0.554)	(0.008,0.091,0.445)
S3	(0.015,0.123,0.548)	(0.051,0.146,0.562)	(0.018,0.089,0.493)	(0.102,0.202,0.614)	(0.040,0.132,0.511)	(0.074,0.188,0.664)	(0.087,0.187,0.588)	(0.068,0.165,0.553)	(0.078,0.199,0.686)	(0.049,0.150,0.557)
S4	(0.042,0.142,0.560)	(0.080,0.167,0.576)	(0.065,0.160,0.587)	(0.019,0.085,0.477)	(0.009,0.083,0.457)	(0.073,0.180,0.647)	(0.050,0.148,0.560)	(0.032,0.125,0.524)	(0.121,0.233,0.683)	(0.048,0.143,0.543)
S5	(0.109,0.191,0.520)	(0.045,0.123,0.480)	(0.010,0.094,0.468)	(0.042,0.124,0.494)	(0.013,0.058,0.347)	(0.063,0.152,0.563)	(0.007,0.059,0.424)	(0.006,0.084,0.435)	(0.065,0.163,0.583)	(0.007,0.088,0.441)
S8	(0.041,0.139,0.544)	(0.077,0.163,0.559)	(0.047,0.142,0.556)	(0.048,0.142,0.552)	(0.009,0.096,0.459)	(0.019,0.092,0.519)	(0.065,0.158,0.543)	(0.064,0.153,0.537)	(0.052,0.165,0.634)	(0.028,0.121,0.512)
S9	(0.043,0.146,0.571)	(0.015,0.107,0.527)	(0.080,0.177,0.611)	(0.083,0.178,0.607)	(0.011,0.102,0.482)	(0.054,0.163,0.642)	(0.022,0.089,0.479)	(0.098,0.189,0.576)	(0.075,0.191,0.681)	(0.049,0.145,0.554)
S10	(0.010,0.090,0.431)	(0.007,0.048,0.387)	(0.009,0.086,0.437)	(0.010,0.056,0.406)	(0.036,0.106,0.410)	(0.043,0.124,0.509)	(0.076,0.149,0.485)	(0.011,0.053,0.348)	(0.029,0.102,0.501)	(0.040,0.113,0.442)
S11	(0.006,0.083,0.400)	(0.010,0.049,0.362)	(0.008,0.050,0.376)	(0.039,0.110,0.431)	(0.001,0.066,0.350)	(0.074,0.148,0.502)	(0.010,0.081,0.395)	(0.008,0.046,0.351)	(0.012,0.065,0.400)	(0.056,0.123,0.412)
S12	(0.039,0.126,0.511)	(0.039,0.118,0.495)	(0.044,0.130,0.523)	(0.014,0.102,0.492)	(0.008,0.057,0.401)	(0.016,0.113,0.546)	(0.078,0.164,0.540)	(0.046,0.127,0.491)	(0.081,0.181,0.624)	(0.011,0.064,0.403)

Table 8 Ranking of the synergies

Synergies	R	D	D + R	D − R	Rank
S1: Energy Efficiency & Sustainability	1.757	1.15	2.907	− 0.606	10
S2: Eco-Friendly Product Lifecycle Management	1.639	1.687	3.327	0.048	7
S3: Supply Chain Collaboration & Visibility	1.767	2.216	3.983	0.449	2
S4: Real-Time Environmental Impact Monitoring	1.778	2.111	3.889	0.333	4
S5: Decentralized Renewable Energy Platforms	1.477	1.732	3.209	0.256	8
S8: Reverse Logistics & Recycling	2.052	2.009	4.061	− 0.043	1
S9: Ethical & Fair-Trade Practices	1.751	2.141	3.892	0.391	3
S10: Responsible Sourcing & Procurement	1.643	1.507	3.15	− 0.137	9
S11: Emission Tracking & Carbon Footprint Reduction	2.216	1.358	3.574	− 0.859	5
S12: Automated Compliance & Reporting	1.641	1.81	3.451	0.169	6

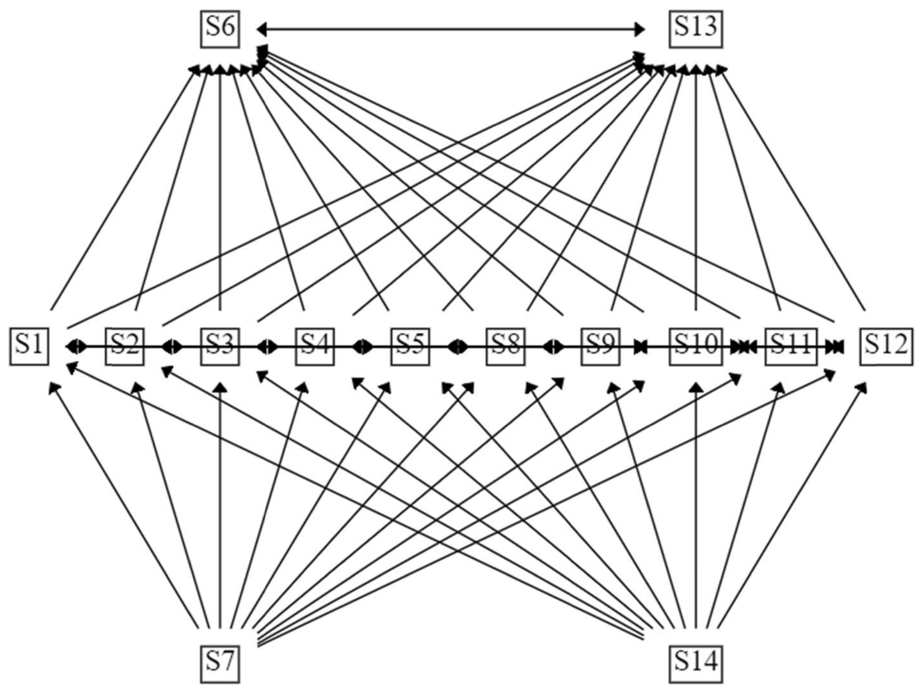


Fig. 1 ISM-based model

Real-Time Environmental Impact Monitoring (S4) ranks high with a D + R value of 3.889 and a D-R value of 0.333, underscoring the essential nature of continuous monitoring for compliance and prompt issue resolution. Implementing real-time monitoring systems helps the industry adhere to environmental regulations and quickly address any environmental concerns. Emission Tracking & Carbon Footprint Reduction (S11), with a D + R value of 3.574 and a D-R value of − 0.859, emphasizes the need for strategies to reduce greenhouse gas emissions, contributing to the industry's sustainability goals. Automated Compliance & Reporting (S12), showing a D + R value of 3.451 and a D-R value of 0.169, highlights the benefits of automation in enhancing efficiency and accuracy in adhering to environmental standards. Eco-Friendly Product Lifecycle Management (S2), identified as a causal variable with a D + R value of 3.327 and a D − R value of 0.048, stresses the importance of managing the product lifecycle with a focus on eco-friendliness to significantly reduce environmental impacts. Decentralized Renewable Energy Platforms (S5), another causal variable with a D + R value of 3.209 and a D − R value of 0.256, underscores the role of renewable energy sources in reducing dependence on fossil fuels and enhancing sustainability.

In conclusion, the Fuzzy DEMATEL analysis identifies key synergies that are crucial for enhancing sustainability in the RMG industry. Reverse Logistics & Recycling, Supply Chain Collaboration & Visibility, and Ethical & Fair-Trade Practices emerge as the most important synergies. The analysis also distinguishes between causal synergies, such as Eco-Friendly Product Lifecycle Management and Decentralized Renewable Energy Platforms, and effect synergies, such as Energy Efficiency & Sustainability and Emission Tracking & Carbon Footprint Reduction. Focusing on these key synergies and

Fig. 2 MICMAC analysis

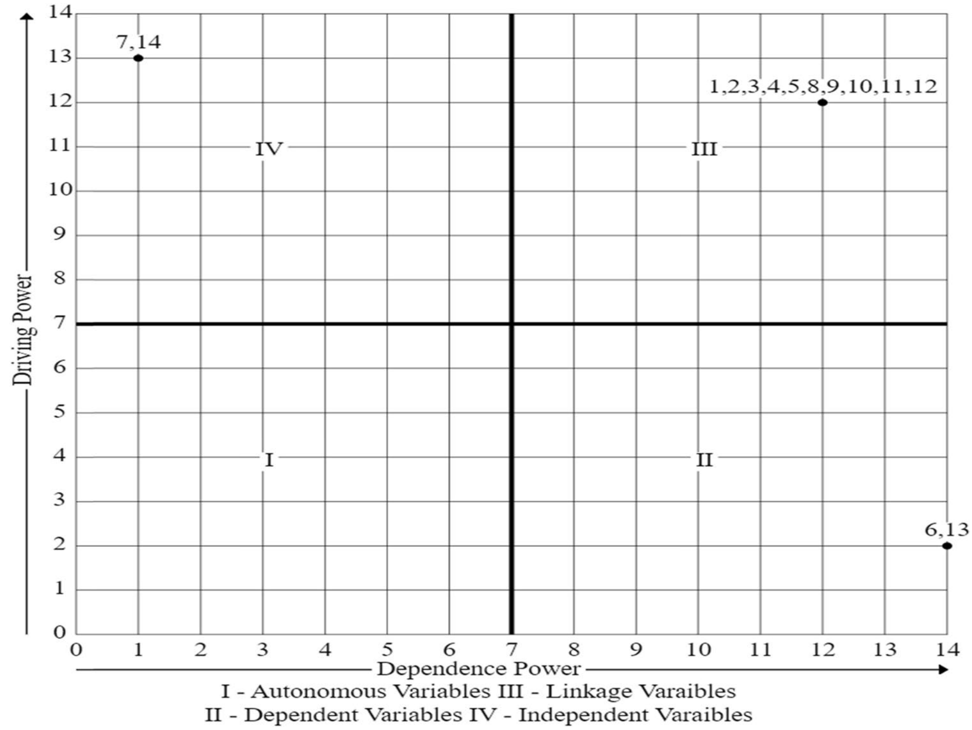
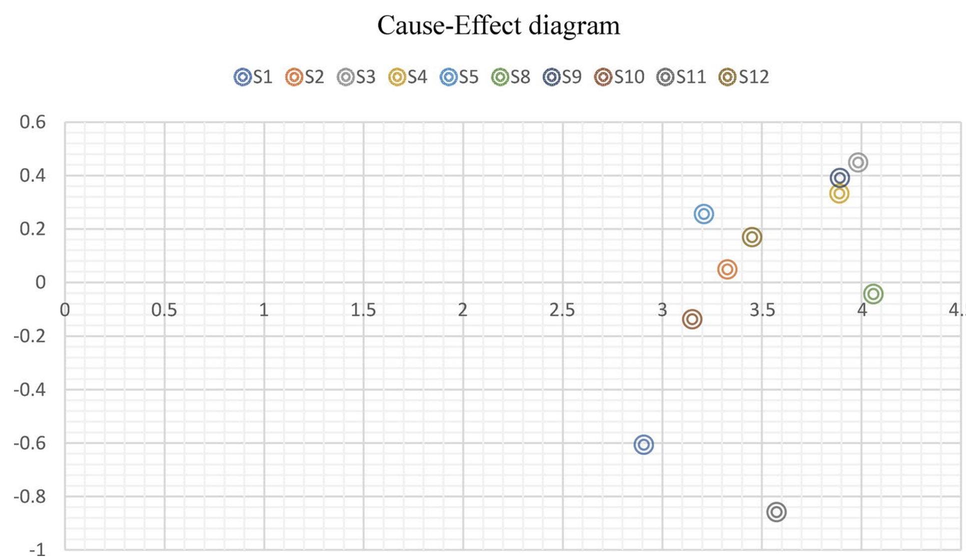


Fig. 3 Cause-effect diagram



their interrelationships can help the RMG industry improve its environmental performance and contribute to sustainable development. The following Fig. 3 shows the model of significant cause-effect relations.

6.4 SDG alignment with this research

The objectives of this research align closely with several Sustainable Development Goals (SDGs), which the Bangladeshi RMG industry seeks to achieve through the integration of BT and I5.0. The following Fig. 4 highlights the SDG alignment with the identified synergies. Key SDGs addressed in this study include SDG 7 (Affordable and Clean Energy), where synergies such as Energy Efficiency & Sustainability and Decentralized Renewable Energy Platforms promote the use of affordable and clean energy sources, improving energy efficiency within the RMG sector. SDG 8 (Decent Work and Economic Growth) is supported through Ethical & Fair-Trade Practices and Responsible Sourcing

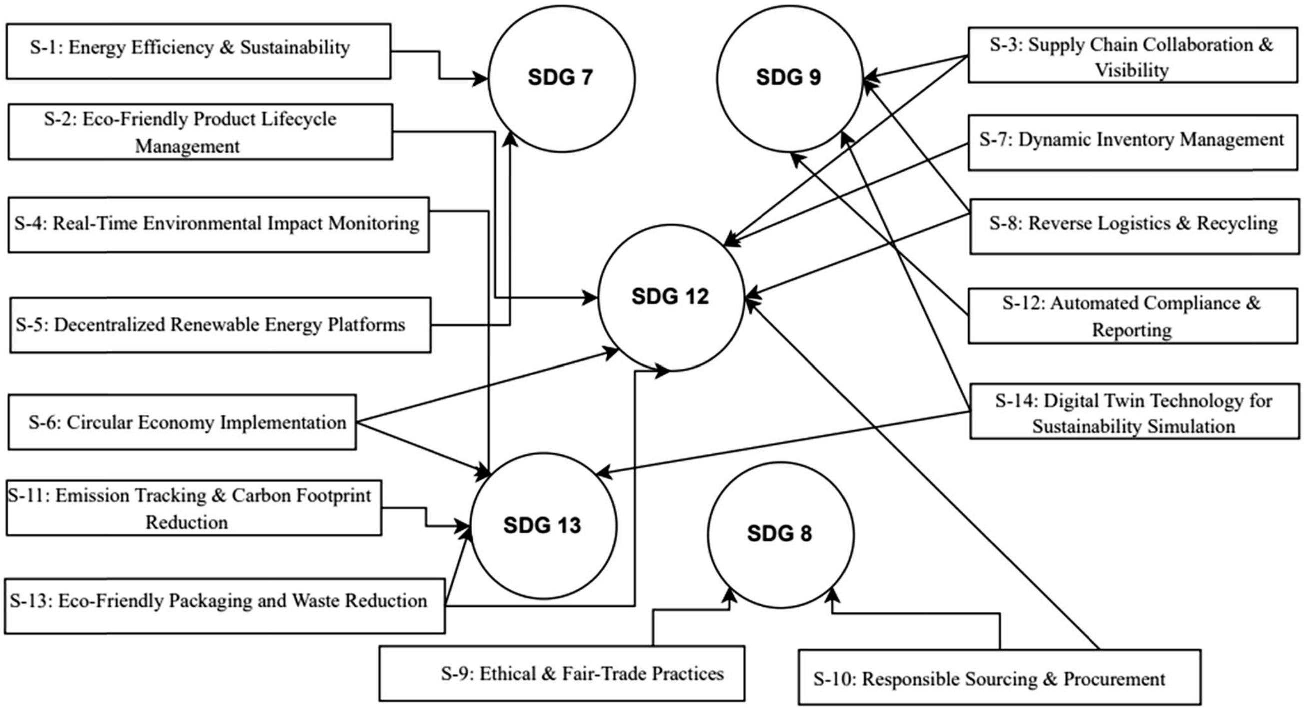


Fig. 4 SDG Alignment with Synergies

& Procurement, which ensure fair labor conditions and ethical sourcing, fostering sustainable economic growth. The research also advances SDG 9 (Industry, Innovation, and Infrastructure) by implementing synergies like Supply Chain Collaboration & Visibility, Automated Compliance & Reporting, and Digital Twin Technology for Sustainability Simulation, which encourage innovation, improve infrastructure, and boost industrial performance. Additionally, SDG 12 (Responsible Consumption and Production) is addressed through initiatives such as Circular Economy Implementation, Dynamic Inventory Management, Reverse Logistics & Recycling, and Eco-Friendly Packaging and Waste Reduction, all aimed at minimizing waste and promoting sustainable practices. Lastly, SDG 13 (Climate Action) is supported through synergies like Real-Time Environmental Impact Monitoring, Emission Tracking & Carbon Footprint Reduction, and Energy Efficiency & Sustainability, which focus on reducing environmental impacts, tracking emissions, and promoting renewable energy to combat climate change. These synergies collectively align with and contribute to the broader global sustainability agenda.

7 Conclusion

This research has provided a comprehensive framework for enhancing sustainability in the Bangladeshi RMG industry through the strategic integration of BT and I5.0. By identifying and analyzing 14 critical synergies using integrated ISM and fuzzy DEMATEL methods. The ISM analysis revealed the hierarchical structure and interdependencies among these synergies, while the Fuzzy DEMATEL approach provided insights into their direct and indirect relationships. The study found that synergies like eco-friendly packaging and waste reduction depend on foundational factors like digital twin technology for sustainability simulation. The integration of BT and I5.0 not only enhances traceability, transparency, and efficiency but also contributes directly to the alignment with several SDGs, such as responsible consumption and climate action. The results offer both generalized and specific outcomes. Generalized outcomes highlight that the synergistic integration of BT and I5.0 can serve as a blueprint for advancing sustainability in other industries beyond RMG. Specific outcomes include actionable insights for stakeholders in the Bangladeshi RMG sector, enabling them to prioritize synergies for immediate implementation, such as improving energy efficiency and promoting circular economy practices.

7.1 Research contributions

This research offers several significant contributions to the field of SSCM and the integration of advanced technologies in the Bangladeshi RMG industry. Through a comprehensive literature review and expert panel discussions, this study identified and refined 14 critical synergies between BT and I5.0. This approach enhances sustainability in the RMG sector. Methodologically, the research employs an integrated approach combining ISM and fuzzy DEMATEL methods, allowing for robust analysis of complex systems. This integration provides a thorough understanding of the interrelationships and influence patterns among the identified synergies through recognizing important drivers, dependencies, and the hierarchical structure of synergies.

The potential of Blockchain and Industry 5.0 technologies to significantly advance these areas is highlighted by aligning the identified synergies with specific Sustainable Development Goals (SDGs), such as Decent Work and Economic Growth (SDG 8), Affordable and Clean Energy (SDG 7), Industry, Innovation, and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13). The findings from the ISM and fuzzy DEMATEL analyses offer practical insights for industry stakeholders, with the identification of independent, dependent, and linkage synergies providing a clear roadmap for prioritizing actions and allocating resources effectively. This structured approach guides the RMG industry in implementing sustainable practices, optimizing supply chain operations, and achieving long-term environmental and economic benefits.

Moreover, this research enhances decision-making frameworks for sustainability initiatives by detailing the interdependencies and driving forces within the system. The clarity offered by the ISM and fuzzy DEMATEL methods enables stakeholders to make informed decisions based on a comprehensive understanding of the cause-and-effect relationships among synergies. This research also adds to the academic discourse on the integration of advanced technologies in traditional industries, particularly in developing countries. The methodological innovations and practical insights presented contribute to the broader body of knowledge on SSCM and technological adoption in the RMG sector.

7.2 Managerial implications

The findings of this research offer valuable managerial insights for decision-makers in the RMG industry, helping to shape effective sustainability strategies. By identifying independent, dependent, and linkage synergies, managers can prioritize initiatives that drive the greatest impact on sustainability outcomes. Understanding the roles of these synergies enables better strategic planning and resource allocation. The study highlights critical linkage synergies such as reverse logistics and recycling (S8), supply chain collaboration and visibility (S3), ethical and fair-trade practices (S9), and responsible sourcing and procurement (S10). Managers should foster collaboration across the supply chain to improve transparency, ethical standards, and responsible sourcing, thereby enhancing sustainable operations.

The integration of Blockchain and Industry 5.0 technologies is pivotal to achieving these sustainability goals. Managers should consider investing in technologies that facilitate real-time environmental impact monitoring (S4), decentralized renewable energy platforms (S5), and digital twin technology for sustainability simulation (S14). These innovations can drive operational efficiency while supporting environmental goals. Moreover, prioritizing initiatives such as reverse logistics and recycling (S8), circular economy implementation (S6), and eco-friendly packaging and waste reduction (S13) will significantly contribute to responsible consumption and production, aligning with SDG 12. Managers should implement policies promoting recycling, waste reduction, and circular economy principles. Automated compliance and reporting (S12) are equally important for meeting regulatory requirements and increasing transparency. Adopting automated systems can streamline compliance processes and ensure the accurate reporting of sustainability metrics. Additionally, focusing on energy efficiency and sustainability (S1), decentralized renewable energy platforms (S5), and emission tracking and carbon footprint reduction (S11) will contribute to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Managers should prioritize energy reduction and emission-control initiatives.

Finally, effective stakeholder engagement is crucial to the success of sustainability initiatives. Managers should involve suppliers, customers, and regulatory bodies in the decision-making process to foster consensus and collaboration. As technology and sustainability practices continue to evolve, the identified synergies and their interdependencies may shift. Continuous monitoring and adaptation will be necessary to ensure the findings remain relevant and actionable in a rapidly changing industry landscape.

7.3 Limitations and future directions

This study is centered solely on the Bangladeshi small and medium sized RMG industry, which may restrict the broader applicability of its findings to other regions or sectors. The distinctive features of the Bangladeshi RMG sector, such as its regulatory framework, market conditions, and socio-economic context, may not align with those in different settings. Future research could address this limitation by conducting comparative studies across various countries or industries to verify and broaden the relevance of the results. Additionally, the reliance on expert opinions for synergy identification and the subsequent ISM and fuzzy DEMATEL analyses introduces a level of subjectivity. Although efforts were made to ensure a diverse and knowledgeable expert panel, the inherent biases and perspectives of the experts could influence the outcomes. Future studies could benefit from incorporating a larger and more diverse group of stakeholders, including practitioners from different levels of the supply chain, policymakers, and end consumers, to provide a more holistic view. The study primarily employs qualitative methods through expert judgment and group discussions. While this approach is valuable for capturing nuanced insights, future research could integrate quantitative methods, such as empirical data analysis and simulation models, to validate and strengthen the findings. Quantitative approaches could provide more objective evidence of the relationships and impacts identified in this study.

Author contributions Md Al Amin contributed to the conceptualization of the research topic, methodology development, and the writing of the original draft, as well as the review and editing of the manuscript. Dr. Roberto Baldacci contributed to the supervision of the research and the review of the manuscript.

Funding Open Access Funding Provided by the Qatar National Library.

Data availability Data is included in the article. The additional data will be available on reasonable requests from the corresponding author.

Declarations

Institutional review board statement The Institutional Review Board of HBKU granted approval for the study under protocol code HBKU-IRB-2024–51 on 13 August 2023.

Informed consent statement The informed consent to participate was obtained from all the participants.

Competing interests The authors declare no competing interests.

Appendices

Appendix A: Reliability, validity, and consistency analysis

See Tables 9, 10.

Table 9 Reliability and item statistics

Reliability statistics		
No. of respondents	Cronbach's Alpha	KMO value
22	0.927	0.638

Item statistics

Synergies	Mean	Std. Deviation	Corrected item-total correlation
S1	3.7273	0.63109	0.707
S2	3.9091	0.81118	0.688
S3	4.0909	0.68376	0.679
S4	3.9545	0.78542	0.513
S5	3.6818	0.64633	0.830
S6	3.9091	0.68376	0.506
S7	3.9091	0.81118	0.736
S8	4.0000	0.75593	0.710
S9	3.9545	0.78542	0.776
S10	4.0909	0.61016	0.554
S11	3.8636	0.77432	0.646
S12	4.1364	0.71016	0.580
S13	3.8182	0.73266	0.699
S14	4.2273	0.61193	0.686

Table 10 Summary of 22 experts under 5 perspectives

Synergies	Perspectives					Pi
	P1	P2	P3	P4	P5	
S1	0	0	17	0	5	0.441558
S2	0	0	2	2	18	0.480519
S3	3	2	17	0	0	0.415584
S4	0	3	2	0	17	0.415584
S5	17	3	2	0	0	0.415584
S6	3	0	3	0	17	0.426407
S7	18	0	2	2	0	0.480519
S8	2	0	2	0	18	0.480519
S9	17	2	3	0	0	0.415584
S10	17	3	0	0	2	0.415584
S11	0	0	2	0	18	0.471861
S12	3	17	2	0	0	0.415584
S13	3	0	0	2	17	0.415584
S14	18	0	2	0	2	0.480519
Pj	0.329	0.10	0.182	0.019	0.371	K = 0.213

Appendix B: ISM method

See Tables 11, 12, 13.

Table 11 Reachability matrix (RM)

Variables	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	Driving power
S1	1	0	1	0	1	0	0	1	1	1	1	1	1	0	9
S2	0	1	0	0	0	0	0	1	0	0	0	0	1	0	3
S3	0	1	1	1	0	0	0	1	1	1	1	0	1	0	8
S4	1	0	1	1	0	0	0	1	0	0	1	1	1	0	7
S5	1	1	1	0	1	0	0	1	0	0	1	0	0	0	6
S6	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2
S7	0	0	0	0	0	0	1	0	0	0	0	1	0	0	2
S8	0	0	0	0	0	1	0	1	1	1	0	0	1	0	5
S9	0	1	1	1	0	1	0	1	1	1	1	0	0	0	8
S10	0	0	1	0	0	1	0	0	1	1	0	0	0	0	4
S11	0	0	0	1	0	0	0	0	0	0	1	1	0	0	3
S12	0	0	1	0	0	0	0	0	1	1	1	1	0	0	5
S13	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2
S14	1	1	0	0	1	0	0	0	0	0	0	0	0	1	4
Dependence Power	4	5	7	4	3	5	1	7	6	6	7	5	7	1	

Table 12 Conical matrix (CM)

Variables	S6	S13	S1	S2	S3	S4	S5	S8	S9	S10	S11	S12	S14	S7	Driving power	Level
S6	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1
S13	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1
S1	1*	1	1	1*	1	1*	1	1	1	1	1	1	0	0	12	2
S2	1*	1	1*	1	1*	1*	1*	1	1*	1*	1*	1*	0	0	12	2
S3	1*	1	1*	1	1	1	1*	1	1	1	1	1*	0	0	12	2
S4	1*	1	1	1*	1	1	1*	1	1*	1*	1	1	0	0	12	2
S5	1*	1*	1	1	1	1*	1	1	1*	1*	1	1*	0	0	12	2
S8	1	1	1*	1*	1*	1*	1*	1	1	1	1*	1*	0	0	12	2
S9	1	1*	1*	1	1	1	1*	1	1	1	1	1*	0	0	12	2
S10	1	1*	1*	1*	1	1*	1*	1*	1	1	1*	1*	0	0	12	2
S11	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1	1	0	0	12	2
S12	1*	1*	1*	1*	1	1*	1*	1*	1	1	1	1	0	0	12	2
S14	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	0	13	3
S7	1*	1*	1	1	1*	1*	1	1*	1*	1*	1*	1*	0	1	13	3
Dependence Power	14	14	12	12	12	12	12	12	12	12	12	12	1	1		
Level	1	1	2	2	2	2	2	2	2	2	2	2	3	3		

Table 13 Reduced conical matrix (RCM)

Variables	S6	S13	S1	S2	S3	S4	S5	S8	S9	S10	S11	S12	S14	S7	Driving power	Level
S6	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1
S13	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	1
S1	1*	1	1	1*	1	1*	1	1	1	1	1	1	0	0	12	2
S2	1*	1	1*	1	1*	1*	1*	1	1*	1*	1*	1*	0	0	12	2
S3	1*	1	1*	1	1	1	1*	1	1	1	1	1*	0	0	12	2
S4	1*	1	1	1*	1	1	1*	1	1*	1*	1	1	0	0	12	2
S5	1*	1*	1	1	1	1*	1	1	1*	1*	1	1*	0	0	12	2
S8	1	1	1*	1*	1*	1*	1*	1	1	1	1*	1*	0	0	12	2
S9	1	1*	1*	1	1	1	1*	1	1	1	1	1*	0	0	12	2
S10	1	1*	1*	1*	1	1*	1*	1*	1	1	1*	1*	0	0	12	2
S11	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1	1	0	0	12	2
S12	1*	1*	1*	1*	1	1*	1*	1*	1	1	1	1	0	0	12	2
S14	0	0	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	0	13	3
S7	0	0	1	1	1*	1*	1	1*	1*	1*	1*	1*	0	1	13	3
Dependence Power	14	14	12	12	12	12	12	12	12	12	12	12	1	1		
Level	1	1	2	2	2	2	2	2	2	2	2	2	3	3		

Appendix C: Fuzzy DEMATEL

See Tables 14, 15.

Table 14 The normalized fuzzy direct-relation matrix

	S1	S2	S3	S4	S5	S8	S9	S10	S11	S12
S1	(0.000,0.000,0.000)	(0.017,0.034,0.069)	(0.034,0.069,0.103)	(0.000,0.000,0.034)	(0.103,0.138,0.138)	(0.000,0.000,0.034)	(0.000,0.000,0.034)	(0.000,0.000,0.034)	(0.034,0.069,0.103)	(0.000,0.000,0.034)
S2	(0.000,0.034,0.069)	(0.000,0.000,0.000)	(0.034,0.069,0.103)	(0.034,0.069,0.103)	(0.017,0.034,0.069)	(0.069,0.103,0.138)	(0.017,0.034,0.069)	(0.017,0.052,0.086)	(0.017,0.052,0.086)	(0.000,0.034,0.069)
S3	(0.000,0.034,0.069)	(0.034,0.069,0.103)	(0.000,0.000,0.000)	(0.086,0.121,0.138)	(0.034,0.069,0.103)	(0.052,0.086,0.121)	(0.069,0.103,0.121)	(0.052,0.086,0.103)	(0.052,0.086,0.121)	(0.034,0.069,0.103)
S4	(0.034,0.069,0.103)	(0.069,0.103,0.138)	(0.052,0.086,0.121)	(0.000,0.000,0.000)	(0.000,0.017,0.052)	(0.052,0.086,0.121)	(0.034,0.069,0.103)	(0.017,0.052,0.086)	(0.103,0.138,0.138)	(0.034,0.069,0.103)
S5	(0.103,0.138,0.138)	(0.034,0.069,0.103)	(0.000,0.034,0.069)	(0.034,0.069,0.103)	(0.000,0.000,0.000)	(0.052,0.086,0.121)	(0.000,0.000,0.034)	(0.000,0.034,0.069)	(0.052,0.086,0.121)	(0.000,0.034,0.069)
S8	(0.034,0.069,0.103)	(0.069,0.103,0.138)	(0.034,0.069,0.103)	(0.034,0.069,0.103)	(0.000,0.034,0.069)	(0.000,0.000,0.000)	(0.052,0.086,0.103)	(0.052,0.086,0.121)	(0.034,0.069,0.103)	(0.017,0.052,0.086)
S9	(0.034,0.069,0.103)	(0.000,0.034,0.069)	(0.069,0.103,0.138)	(0.069,0.103,0.138)	(0.000,0.034,0.069)	(0.034,0.069,0.103)	(0.000,0.000,0.000)	(0.086,0.121,0.138)	(0.052,0.086,0.121)	(0.034,0.069,0.103)
S10	(0.000,0.034,0.069)	(0.000,0.000,0.034)	(0.000,0.034,0.069)	(0.000,0.000,0.034)	(0.034,0.069,0.103)	(0.034,0.069,0.103)	(0.069,0.103,0.138)	(0.000,0.000,0.000)	(0.017,0.034,0.069)	(0.034,0.069,0.103)
S11	(0.000,0.034,0.069)	(0.000,0.000,0.034)	(0.000,0.000,0.034)	(0.034,0.069,0.103)	(0.000,0.034,0.069)	(0.069,0.103,0.138)	(0.000,0.034,0.069)	(0.000,0.000,0.034)	(0.000,0.000,0.000)	(0.052,0.086,0.103)
S12	(0.034,0.069,0.103)	(0.034,0.069,0.103)	(0.034,0.069,0.103)	(0.000,0.034,0.069)	(0.000,0.000,0.034)	(0.000,0.034,0.069)	(0.069,0.103,0.138)	(0.034,0.069,0.103)	(0.069,0.103,0.138)	(0.000,0.000,0.000)

Table 15 The crisp total-relation matrix

	S1	S2	S3	S4	S5	S8	S9	S10	S11	S12
S1	0.086	0.115	0.146	0.093	0.197	0.105	0.079	0.077	0.17	0.082
S2	0.154	0.115	0.186	0.188	0.137	0.235	0.159	0.165	0.199	0.149
S3	0.189	0.21	0.158	0.262	0.189	0.259	0.245	0.223	0.271	0.21
S4	0.206	0.23	0.226	0.152	0.145	0.251	0.212	0.188	0.298	0.204
S5	0.24	0.181	0.157	0.185	0.108	0.219	0.122	0.143	0.231	0.146
S8	0.201	0.224	0.207	0.207	0.154	0.165	0.217	0.212	0.238	0.182
S9	0.21	0.175	0.242	0.243	0.161	0.237	0.155	0.246	0.265	0.207
S10	0.146	0.107	0.145	0.117	0.156	0.188	0.204	0.104	0.171	0.168
S11	0.136	0.103	0.106	0.164	0.114	0.207	0.134	0.099	0.123	0.171
S12	0.188	0.18	0.194	0.166	0.116	0.184	0.222	0.186	0.251	0.122

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