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What Strengthens Social Sustainability in Logistics in the Age of Industry 4.0? Analysis and Modelling of the Enablers

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Abstract
Managing the logistics sector from a sustainability perspective represents an important challenge, which is even more difficult to practice under Industry 4.0 technologies regime. This study investigates the question of what enablers can be there that can be useful for social sustainability in the age of Industry 4.0. In this study, first, important social sustainability factors were assimilated from literature and secondary data derived from industry reports. In the second step, these factors were classified into five categories related to social sustainability enablers (SSEs) using principal component analysis (PCA). Finally, to support the decision makers, the critical SSEs are synthesized using the Fuzzy DEMATEL approach to find the importance of these factors concerning sustainability in logistics operations. The result shows that the use of green technologies related to Industry 4.0 is the most important aspect that derives social sustainability in logistics. The next important critical factor found was promoting social sustainability, the economic aspect, and the safety and well-being of people involved in logistics operations. The critical factor will further help in achieving human-centric automation, fair & inclusive logistics in the era of Industry 4.0.

Keywords- Social sustainability enablers, Logistics management, Industry 4.0, Critical social sustainability factors, Fuzzy method, Sustainability in logistics.

1. Introduction

Social sustainability in logistics is becoming increasingly important as it can improve a company's performance and the well-being of society both (Thacker et al., 2019). Social sustainability is about respect for human life, particularly at the workplace (Hussain et al., 2018). Sustainable development also aims to help people escape poverty by meeting their basic needs, including access to food, clean water, and good education and medical care (Bocken et al., 2016; Thacker et al., 2019). A use case example is reverse logistics, which saves resources and helps society by closing the loop in supply chain (Manaugh et al., 2015). Implementing sustainability in logistics has many advantages, like saving energy and resources, extended product life cycle management, etc. Social sustainability has become essential in our rapidly changing world where environmental, economic and social issues are intertwined (Croom et al., 2018).

The economy needs the inclusion of sustainability in logistics operations (Croom et al., 2018). We must understand that it is logistics that move the economy and is a key driver of growth. But this can also be blamed for emissions and vehicle pollution (Narula et al., 2021). Companies' dilemma is how to improve sustainability without increasing supply chain costs, which may be possible through engineering and technology. Thus, more effective use of resources, elimination of waste, and reduction of operational costs are standard parts of sustainable practices (Manaugh et al., 2015). Hence, integrating technologies with social sustainability offers an opportunity to create an industrial environment that is more equitable, inclusive and socially responsible (Mittal and Obaid, 2023; Vafadar et al., 2021).

Industry 4.0 (I4.0) represents a promising way to combine engineering and technology with responsibility. I4.0 is central to circular social solutions for business processes (Upadhyay et al., 2023). But technical difficulties and challenges in the introduction of I4.0 technologies must be identified (Sharma et al., 2023b). The impact of I4.0 technologies extends to waste reduction through optimised operations, improved resource management and informed decision making facilitated by real-time data (Kirmizi and Kocaoglu, 2022). However, I4.0 goes beyond the supply chain and covers every aspect of the product journey (Rossini et al., 2023). We therefore examined the social sustainability factors termed as '*Social Sustainability Enablers* (*SSE*)' in the context of the logistics industry. This is also important because several SDGs are particularly relevant in the context of social sustainability in logistics. SDG 1, which reflects freedom from poverty, is directly related to employment in the logistics sector. However, achieving sustainable cities (SDG 11) and responsible consumption and production (SDG 12) are also crucial, and I4.0 will play a crucial role. Thus, I4.0 offers a crucial convergence that could change the way we think about social sustainability.

No wonder governments, businesses and civil society need to work together and develop diverse strategies to address these social security issues (Stiglitz, 2021). The way forward to implement social sustainability in logistics systems involves the need to ensure compliance with laws, external organisations, society and government. The impact and technological advancements were discussed about corporate societal factors and automation of work processes (Natee et al., 2021). They explained the automation in smart warehouses concerning social sustainability for the modern era. The research also emphasised the need to explore the balancing of automation and human roles in the I4.0 governed logistics operations (Sharma et al., 2024). A systematic literature review on social sustainability in the age of digitalization also emphasizes the humancentric implications of the workforce in I4.0 operations (Grybauskas et al., 2022). It also insisted on the need for studies based on social factors given efficient working environments in digitally governed industries. The circular approach for achieving social sustainability in industrial operations in the I4.0 for providing ecological growth of the organization and workforce is discussed in the study (Bai et al., 2022). They also emphasize the need for primary data collection and providing more empirical studies on social sustainability. The green human resource practice in logistics 4.0 is presented in the study and explains the digital analytics roles in logistics social responsibility (Jaaron et al., 2025). The study tries to fill the gap in green technologies and social responsibility but is more focused on data analytics. It shows the need to explore the importance of other I4.0 technologies.

Understanding these SSEs is crucial for developing effective strategies to improve social sustainability in the logistics sector and keeping it in line with the growing importance of sustainability. The transformative shift in modern logistics networks created the need to study empirically the social sustainability role in the industrial revolution. The advanced need for skills raises serious questions regarding the sustainability of society even as they increase production and efficiency. Long-term societal stability depends on ensuring equal service practices, advancing worker well-being, inspiring inclusive economic growth, and upholding moral corporate comportment (Jaaron et al., 2025). The major challenge is in locating and incorporating societal enablers that promote moral and crucial decision-making as firms embrace smart technology at an increasing rate (Grybauskas et al., 2022). Enterprises face threats of missing important social factors that support sustainable growth if they don't have a thorough grasp of these enablers. The study focuses on investigating the key factors that support social sustainability in the age of I4.0 and evaluating effective business choices. The research study tries to answer the following research questions (RQ):

***RQ*1:** What are the social sustainability enablers in logistics management of the I4.0 era?
***RQ*2:** What are the crucial social sustainability enablers that influence efficient business decisions, and how can they be analysed for importance?

The study tries to investigate the above questions. The subsequent section presents the literature review.

2. Literature Review

2.1 I4.0 Technologies and Logistics Management

The assembly line, the invention of the steam engine, and computer-controlled systems were all significant inventions of the last three industrial revolutions (Schiele et al., 2022). The fourth industrial revolution i.e. I4.0, uses effective and intelligent technologies to revolutionise industrial processes. Cyber-physical systems (CPS) and the Internet of Things (IoT) are intelligent, self-managed systems that form the foundation of I4.0 (Thames and Schaefer, 2016). Companies are rapidly adopting new technologies of Industry 4.0 (I4.0), including artificial intelligence (AI) in their processes (Khan et al., 2023a). The integration of social factors in I4.0 has evolved and is increasingly recognised as a critical dimension (Saha et al., 2020). Initially, I4.0 focused primarily on technological advances and automation. Digitalisation brings many decisive advantages and significantly increases efficiency in Logistics 4.0 for last-mile delivery. Some studies have been researched on industrial revolutions and the environmental impact on Logistics 4.0 (Monostori et al., 2016).

However, as the paradigm matured, it became clear that the social dimension played a crucial role in its success. For several compelling reasons, social sustainability is of utmost importance in today's industrial work culture (Saha et al., 2020). The researchers had presented many studies in the I4.0 technology context, but research gaps in social sustainability still required further scientific investigation. And it is needed to identify and resolve the ethical concerns in I4.0 as well. But, incorporating social factors into technological breakthroughs requires more extensive research to evaluate existing solutions and identify areas for improvement. We can say that these are some gaps that will contribute towards resilient and responsible logistics management.

2.2 Social Sustainability and Logistics

Logistics performance is linked to the social dimension of sustainability, which includes health, education, equality and personal income distribution (Larson, 2021). Social sustainability includes all procedures, regulations and principles that promote the well-being of the workforce, the neighbourhood and society. Promoting a work environment prioritising employee safety and overall well-being is key to social sustainability (Carayannis and Morawska-Jancelewicz, 2022). Employees who feel empowered and respected are more likely to propose and adopt new ideas, which helps companies remain competitive and responsive to environmental needs (Alblooshi et al., 2021). Effective collaboration and communication among many stakeholders, including employees, managers, legislators and community leaders, are critical to achieving social sustainability in the logistics sector. Engineering and technology benefits people, but they must adapt to new procedures and skill levels, which can be difficult. Rapid technological advances and restructuring of business processes can increase employee stress, job insecurity or dissatisfaction. Addressing these issues is necessary to maintain a long-lasting and productive workforce.

2.3 I4.0 Technologies and Social Sustainability

Understanding the complex dynamics between stakeholders and the challenges they pose to achieving socio-technical contributions is crucial when talking about human components in I4.0 systems. Human engagement is crucial for effectively installing and operating I4.0 technologies (Passalacqua et al., 2024). I4.0 introduces new ways and places for relationships but also requires a paradigm shift towards openness, inclusion, and shared decision-making (Samaranayake et al., 2024). Furthermore, it is crucial to consider the ethical issues related to data privacy and security and the environmental impact of logistical operations (Sharma et al., 2022). We have compiled a summary of current studies and trends in social sustainability, shown in **Table 1**. Readers are advised to refer to some detailed literature reviews provided by Vrchota et al. (2020) on green processes (logistics, production and brand design) and technology implementation issues, Bader et al. (2020) about society operating in the I4.0 environment. A closer look at the literature reveals several gaps and shortcomings in technological improvements for the socially sustainable adoption of I4.0 technologies in the logistics sector.

Table 1. Recent developments in social sustainability in the I4.0 era.

S. No.	Author and year	Purpose	Method	Research findings
1.	Khan et al. (2023b)	This study focuses on examining the crucial elements of Logistics 4.0 success.	DEMETAL	The critical aspect of leadership commitment and goal aligning for logistic 4.0 discussed.
2.	Ghadge et al. (2022)	Demonstrate the connection between the theoretical frameworks of I4.0 and green supply chain management.	ISM and SEM	The study discovered a more vital link between I4.0 and GSC adheres in the vehicle manufacturing supply chains and an indirect impact of I4.0 technology on GSC performance via GSC practices.
3.	El Hamdi, & Abouabdellah (2022)	This article aims to clarify how the previous industrial revolution affected the development of logistics.	Bibliographic literature review	This essay discusses the relationship between I4.0 and Logistics 4.0. Increased digital connectivity, visibility, physical distribution centers with reliable and speedy delivery options, improved logistics capacity, and a less harmful environment.
4.	Shayganmehr et al. (2021)	The current study investigates I4.0 enablers to assess security and privacy concerns.	Exploratory factor analysis	It is related to I4.0 systems of IT that depend upon social platforms related to business ethics. The study discusses the concerns and problems associated with ethical data management.
5.	Raj and Sah (2019)	This article examines the obstacles to the industrial sector's integration of I4.0 technology in developed and developing nations.	Grey-DEMATEL	The main barriers of adopting I4.0 are the lack of a digital approach and resource shortages in developed and emerging nations.
6.	Frank et al. (2019)	This article explains how industrial businesses are utilising I4.0 technology.	Descriptive study	According to our study, the front-end technologies-of which Smart Manufacturing is crucial-are linked to the widespread industry adoption that results in I4.0. Considering that analytical methods and big data are still not extensively employed in the population of interest, our findings also show how challenging it is for firms to use essential technologies.
7.	He et al. (2018)	Literature review on logistics to examine the influence of logistics sustainable development.	Descriptive analysis	The study's findings serve as a reference point for academics studying logistics space and architects planning logistics facilities. They also aid in creating fresh logistics development plans and advancing logistics sustainable growth.
8.	Speranza (2018)	To determine the trends of I4.0 technologies in the logistics sector.	Muti criteria decision-making	This essay will briefly explore the history of issues OR contributions in logistics and, transportation, and technology development.

Table 1 Continued…

9.	Mashhadi and Behdad (2017)	Steps to close the gap between technology and environmental assessment	Statistical conventional life cycle assessment (LCA) techniques	The synergy of intelligent manufacturing with LCA is addressed to deliver improved assessment and decision-making.
10.	Wang et al. (2016)	Mathematical framework of min-cost flow problems given and offer some pruning techniques that can drastically reduce the network size.	min-cost travel problem and distinctive trimming strategies	This work proposes a productive, substantial mobile crowd-tasking strategy using a considerable volunteer pool for last-mile delivery. To formulate the model as a network that may drastically minimise the network size to solve it effectively. Many tests were conducted using datasets from Beijing and Singapore.
11.	Clausen et al. (2016)	The initiative advocated Urban Consolidation Centres (UCCs), which permit and encourage modal change in addition to transportation consolidation.	Survey/empirical method	The primary takeaways from the research are the examples of UCCs as potential last-mile solutions. Beyond their economic success, their social and environmental repercussions were assessed. Large trucks are employed for packaged, long-distance transfers outside the city, while sustainable transport methods are used inside, decoupling the final mile at the city limits.
12.	Faccio and Gamberi (2015)	This project focuses on creating a new eco-logistic system that transports cargo between cities utilising electric cars.	Empirical study	Compared to the identical distribution carried out by diesel or methane vehicles, there is an approximate 84% reduction in CO_2 equivalent emissions. Focus on logistics and environmental concerns.

Source: authors

3. Methodology

The research utilises a thorough, three-stage methodology specifically designed to assess the critical components of social sustainability in logistics enabled by I4.0. The study combines descriptive and empirical methods to assess SSE. The three separate stages of the research method are explained below in **Figure 1**.

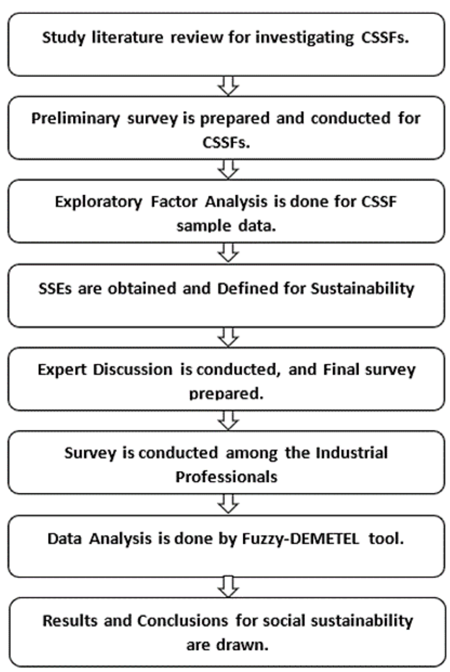

Figure 1. Research methodology steps (Source: created by authors).

The three broad stages can be summarised as follows.

i. Identification of critical social sustainability factors (CSSF) for logistics.
ii. Deriving the SSEs from CSSF using statistical analysis.
iii. Identifying and analysing the prominent SSEs using Fuzzy-DEMETAL approach.

3.1 Stage-1- Critical Factor Identification

In the first step of this study, potential factors related to social sustainability were identified from the existing scientific literature based on Narula et al. (2021), Ocampo et al. (2020) and Prakash et al. (2022). The latest research articles published in English are from the Scopus and Google Scholar databases, period was 2015 to 2023. The two-member research team selected the contextual articles by manually reading the abstract title and keyword. Coding was used to extract the factors, creating a comprehensive list of possible factors. Discussions with academic experts and two previously involved researchers resulted in the final list of critical factors for social sustainability. The reason for using this method was that I primarily use published, peer-reviewed research articles that ensure the quality of the factors identified for this work. The opinion of industry experts was not taken into account at this time as this comprehensive list and subsequent survey related to these straps followed in the next section. **Table 2** presents the list of assimilated factors of social sustainability in logistics.

Table 2. Critical social sustainability factors (CSSF) in logistics.

Factor No.	Factor name and reference	Definition
CSSF1	Resource efficiency (Sun et al., 2023; Wang et al., 2022; Xu et al., 2023).	Minimising waste and maximising production to optimise resources in a particular process or system refers to resource efficiency.
CSSF2	Income stability for employees in the logistics sector (Chen and Kong, 2023; Margherita and Braccini, 2021).	Resource efficiency is refining the use of resources in a given process or system to reduce waste and increase productivity. It entails assessing and optimising the use of resources to support sustainable practices and economic viability.
CSSF3	Social responsibility and ethical/fair labor conditions (Nantee and Sureeyatanapas, 2021; Saniuk et al., 2022).	Social responsibility is moral behaviour that considers stakeholders, communities, and workers' well-being. The research emphasises evaluating efforts to ensure ethical, sustainable, and socially responsible supply chains.
CSSF4	Community well-being and employee well-being (Chute and French, 2019; Saniuk et al., 2022; Sartal et al., 2020).	In the context of supply chains and logistics, community well-being assesses how industry operations affect the communities in which they are located. It focuses on positive and sustainable interactions and examines how supply chain practices can support or undermine community health.
CSSF5	Quality of jobs created or retained (Asif, 2020; Haleem et al., 2023; Salvadorinho and Teixeira, 2023).	The quality of jobs refers to the type of jobs created or maintained by industry activity, having stability and scope for progress.
CSSF6	Income and earnings improvement (Haleem et al., 2023; Salvadorinho and Teixeira, 2023; Saniuk et al., 2022).	Strategies to increase financial security for both individuals and organisations are the main emphasis of income and earnings enhancement. This involves looking into ways to improve the logistics industry's overall economic performance, cut costs, and increase productivity.
CSSF7	Environmental impact and green logistics (Jamkhaneh et al., 2022; Parhi et al., 2022; Sharma et al., 2023a).	Environmental impact refers to how industry operations affect natural resources and ecosystems. This field of study aims to recognise and address environmental issues while advancing sustainable practices and reducing the environmental impact of supply chain operations through green logistics.
CSSF8	Supply chain resilience (Patidar et al., 2023; Spieske and Birkel, 2021; Tortorella et al., 2022).	Supply chain resilience refers to analysing supply chains' capacity to endure shocks and bounce back. Analysing risk management techniques, integrating technology, and making backup plans are all part of improving the supply network's overall resilience.
CSSF9	Data Security and Privacy (Gupta et al., 2020; Hammad et al., 2023; Liu et al., 2020).	Critical information must be protected throughout the supply chain process, making data security and privacy crucial factors in the logistics and supply chain industry. Research ensures the integrity and confidentiality of data throughout the logistics network by addressing data security concerns and solutions.
CSSF10	I4.0 Technologies with ERP (Bartosik-Purgat et al., 2022; Fiorini et al., 2022; Trappey et al., 2016).	I4.0 technology combined with Enterprise Resource Planning (ERP) systems entails the digital transformation of logistics processes in supply chains and logistics. Research examines the uptake and effects of various technologies to improve supply chain efficiency, visibility, and decision-making.

Table 2 Continued…

CSSF11	People's economic status (Al Kurdi et al., 2020; McGee and Benk, 2023; Salvadorinho and Teixeira, 2023).	The financial health of people impacted by industrial operations is called people's economic status. This research investigates how the areas they serve are affected by logistics activities in terms of employment prospects, income distribution, and general economic health.
CSSF12	Social security concerns (Bartosik-Purgat et al., 2022; Dwivedi et al., 2023; Saniuk et al., 2022).	Social security concerns relate to matters of worker and community support and protection. Research ensures the welfare of those impacted by logistical operations by addressing issues and suggesting enhancements to social security systems.
CSSF13	Skills for I4.0 Systems (Agarwal and Ojha, 2022; Kargas et al., 2022; Tortorella et al., 2022).	Skills for I4.0 systems focus on the abilities needed to operate and take advantage of cutting-edge technologies. Skills gaps must be identified and filled to guarantee that the workforce is sufficiently prepared to manage the integration of I4.0 technologies in logistics operations.
CSSF14	Sustainable Supply Chain initiatives (Jamkhaneh et al., 2022; Parhi et al., 2022; Sharma et al., 2023b).	Sustainable supply chain initiatives incorporate socially and ecologically conscious practices into supply chain operations. Studies investigate the efficacy of sustainability initiatives, pinpoint optimal methodologies, and provide approaches for advancing sustainability in the logistics industry.
CSSF15	Technology for Human Resource (Agarwal and Ojha, 2022; Fiorini et al., 2022; Panagou et at., 2021).	Digital tools are employed to optimise HR procedures, termed technology for human resources. This involves investigating how technology affects training, personnel management, and the general effectiveness of human resources in logistical operations.
CSSF16	Technical skills required for I4.0 (Agarwal and Ojha, 2022; Lemstra and de Mesquita, 2023).	The precise competencies required to run sophisticated technologies are referred to as "technical skills required for I4.0" in supply chain and logistics research. The research tackles skill gaps and training demands.
CSSF17	Skills for disruptive technologies (Buhalis et al., 2023; Scuotto et al., 2022).	The skills necessary to manage and utilise emerging technologies that potentially transform industry practices are disruptive technologies skills in supply chain and logistics research. This involves researching the skill sets required of people to flourish in a setting impacted by disruptive technology in logistics operations.

Source: authors

Determining the impact of these 17 CSSFs on logistics management in I4.0 is challenging. There will be an interplay between the factors, so the individual assessment of each factor and the phenomena of social sustainability logistics will be incomplete and confusing. In order to make the research more effective and achieve the desired objective of RQ1, we decided to survey the industry so that factors can be consolidated and classified. To conduct empirical research, the researchers designed a survey questionnaire and sent it to the industries operating in the logistics sector and using the sum or other I4.0 technologies. The questions were asked about the 17 factors identified above. The survey was conducted online and offline (see Appendix I) and was sent to the contextual respondents in July 2022. Initially, 143 responses were received; the researcher conducted another round of data collection and a total of 194 responses were received. Duplicate and incomplete answers were deleted and finally 173 responses were used for analysis.

Respondents included a diverse mix of business types from supply chain and logistics functions, such as manufacturing (40%), retail (10%), transportation (28%) and logistics service providers (15%), with the remaining respondents representing other industries. Geographically, there were responses from various regions, including 58% from India, 12% from Europe, and 15% from Asia (except India) and rest from various global locations. Demographically, the respondents represented a broad age with 25% below 30 years, 35% between 30 and 40 years, and 40% over 40 years. In terms of educational background, 20% held diplomas, 65% were graduates, 10% had postgraduate degrees, and 5% possessed Ph.D. qualifications, reflecting a well-educated workforce. The job roles of respondents spanned across various levels, such as engineers, managerial positions, senior executives, consultants, vice presidents and plant heads, and academicians ensuring insights from both early-career professionals and seasoned decision-makers.

3.2 Stage 2- Exploratory Factor Analysis (EFA) for Obtaining SSEs

The survey data of 173 of the 194 respondents are considered for EFA, the reliability test is carried out and Cronbach's alpha and KMO and Bartlett tests were satisfactory. Principal component analysis was the extraction method, and it interprets CSSF 1 as the most likely principal element, followed by CSSF 2 and CSSF 3 (source scree plot, **Figure 2**). **Table 3** shows the rotated component matrix for CSSF obtained from EFA. To emphasise factor independence, varimax rotation with Kaiser normalisation was used. The rotated component matrix shows that each component captures specific factors and that their correlations have little overlap. CSSF1, CSSF2, CSSF11, CSSF12 and CSSF13 appear to be widespread and contribute to multiple components. **Table 3** shows the rotated component matrix for CSSFs.

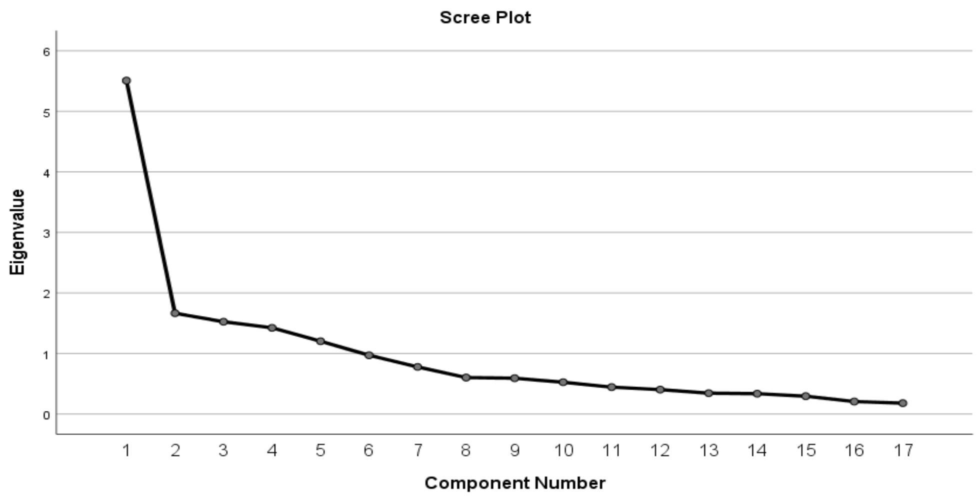

Figure 2. Scree plot for CSSFs (Source: created by authors).

Table 3. Rotated component matrix for CSSFs (Source: Author).

Rotated component matrix					
CSSF No.	Component				
	1	2	3	4	5
1.	0.408	0.625			
2.	0.358	0.782			
3.		0.779			
4.		0.739			
5.			0.827		
6.			0.833		
7.	0.314				0.734
8.					-0.76
9.	0.872				
10.	0.824				
11.	0.668	0.324			
12.	0.689	0.482			
13.	0.73	0.369			
14.	0.619				
15.	0.647				
16.				0.829	
17.				0.858	
a. Rotation converged in 6 iterations.					

Formation of SSE: Thus, after carrying out the EFA on the CSSFs, the dominant SSEs for sustainability are identified. These are categorised into five main categories of SSEs according to the principal component analysis (PCA) results, as shown in **Table 4**.

Table 4. Five major clusters/categories termed as SSE.

I4.0 Technologies with ERP	People economic status	Social security concerns and employee well-being	Skills for I4.0 systems	Sustainable supply chain initiatives
Category- SSE1	**Category- SSE2**	**Category- SSE3**	**Category- SSE4**	**Category- SSE5**
*CSSF*9	*CSSF*5	*CSSF*1	*CSSF*16	*CSSF*7
*CSSF*10	*CSSF*6	*CSSF*2	*CSSF*17	*CSSF*8
*CSSF*11		*CSSF*3		
*CSSF*12		*CSSF*4		
*CSSF*13				
*CSSF*14				
*CSSF*15				

These five categories of CSSFs are then referred to as SSEs (see **Table 5**).

Table 5. I4.0 SSEs descriptions.

S. No.	SSEs	Source	Code	Description
1.	I4.0 green technology	Fiorini et al. (2022), Trappey et al. (2016)	SSE1	Smart systems integrating green technology in I4.0 optimise energy consumption, decrease waste, and prioritise green practices, supporting social sustainability. I4.0-governed high-tech synergy helps enterprises and promotes better conditions for the environment and local communities.
2.	People economic status	Al Kurdi et al. (2020), McGee and Benk (2023)	SSE2	In I4.0, workers, rather than being substituted by robots, will have many new job opportunities in the justified tasks that can be automated. Lower product pricing and more consumption may come from reduced logistics costs, significantly enhancing the economy. It may increase demand for employment using automation.
3.	Social security concerns and employee well-being	Panagou et al. (2021), Parmentola et al. (2021)	SSE3	As I4.0 technologies like the IoT, cloud computing, 3D printing, and genetic editing increase, the issues and impacts linked to data safety, algorithmic bias, discernment, and privacy are exponentially growing. These innovations in digital and AI capabilities form the foundation of these technologies.
4.	Skills for I4.0 systems	Agarwal and Ojha (2022), Kargas et al. (2022), Vaiman et al. (2012)	SSE4	Jobs are no longer as simple as once; most jobs now require various talents and duties. The low-skilled, routine duties that are most at risk of being replaced by automation will require replacing existing staff with new, highly skilled employees, focusing on management, quality control, and increased supervision.
5.	Eco-friendly supply chain initiatives	Attah-Boakye et al. (2022), Ahmed et al. (2020)	SSE5	Captures sustainable production where supply-chain managers have much freedom to adopt green practices. The green and sustainable supply chain that helps achieve green logistics management in totality.

Source: Authors

Finally, five SSEs reflect sustainable practices in the logistics sector in the I4.0 environment. We must prioritise these SSEs in the next phase to identify focus areas.

3.3 Stage 3- Fuzzy-DEMETAL to Identify the Prominent Factors

The next step is to prioritise these SSEs. The birth of Multi-Criteria Decision-Making (MCDM) assisted managers in decision-making processes by considering multiple criteria at the same time. There are several methods like TOPSIS, ANN, AHP, Vikors, DEMATEL etc. which are utilised for MCDM, this study uses Fuzzy DEMATEL is used as research tool for identifying the role of key factors in the Supply chain and allied areas. (Lin et al., 2018; Raj and Sah, 2019; Zhou et al., 2011). Fuzzy DEMATEL is often chosen to handle the complexity and uncertainty of a decision-making process. It was suitable for us because we collected the data for the I4.0 environment, which is still in the development phase for many industries and experts. In the next step, we present the application of the method. A total of eight experts participated in the input-giving round on Fuzzy DEMATEL.

Step 1: ***Fuzzy DEMATEL Method Application***

In step 1, a fuzzy direct-relation matrix (DRM) is created. Initially, the $n \times n$ matrix is generated to ascertain the model of relationships among the n-criteria. The influence of each element in a row on each element in a column of this matrix can be represented as a fuzzy number. Every specialist must complete the matrix if multiple expert downright rights are used.

Here,

DRM $A = \begin{bmatrix} 0 & \cdots & A_{n1} \\ \vdots & \ddots & \vdots \\ A_{1n} & \cdots & 0 \end{bmatrix}$...... its arithmetic mean of all expert inputs.

Table 6 presents the DRM as a pairwise comparison matrix of the expert inputs and **Table 7** shows the fuzzy scale used in the study.

Table 6. Direct relation matrix (DRM).

	Quality of life	Economic status	Government policies	Environmental conditions
Quality of life	(0.00,0.00,0.00)	(6.00,7.00,8.00)	(2.00,3.00,4.00)	(6.00,7.00,8.00)
Economic status	(8.00,9.00,9.00)	(0.00,0.00,0.00)	(4.00,5.00,6.00)	(6.00,7.00,8.00)
Government policies	(6.00,7.00,8.00)	(6.00,7.00,8.00)	(0.00,0.00,0.00)	(8.00,9.00,9.00)
Environmental conditions	(6.00,7.00,8.00)	(2.00,3.00,4.00)	(6.00,7.00,8.00)	(0.00,0.00,0.00)

Table 7. Fuzzy scale.

Code	Linguistic terms	L	M	U
1	‘Scale given was- No influence’	1	1	1
2	‘Scale given was- Very low influence’	2	3	4
3	‘Scale given was- Low influence’	4	5	6
4	‘Scale given was- High influence’	6	7	8
5	‘Scale given was- Very high influence’	8	9	9

Step 2: ***Normalise the fuzzy DRM***

The normalised fuzzy DRM can be obtained using the following formula:

$$P_{fg} = \frac{\tilde{A}_{ifg}}{w} = \left(\frac{l_{fg}}{w}, \frac{m_{fg}}{w}, \frac{u_{fg}}{w}\right),$$

where, $w = \max_{f,g}\left\{\max_{f} \sum_{g=1}^{n} u_{fg}, \max_{g} \sum_{g=1}^{n} u_{fg}\right\} \; f, g \in \{1,2,3, \dots, n\}$.

Table 8 below presents normalised fuzzy DRM.

Table 8. Normalised fuzzy direct relation matrix.

	Quality of life	Economic status	Government policies	Environmental conditions
Quality of life	(0.00,0.00,0.00)	(0.24,0.28,0.32)	(0.08,0.12,0.16)	(0.24,0.28,0.32)
Economic status	(0.32,0.36,0.36)	(0.00,0.00,0.00)	(0.16,0.20,0.24)	(0.24,0.28,0.32)
Government policies	(0.24,0.28,0.32)	(0.24,0.28,0.32)	(0.00,0.00,0.00)	(0.32,0.36,0.36)
Environmental conditions	0.24,0.28,0.32	(0.08,0.12,0.16)	(0.24,0.28,0.32)	(0.00,0.00,0.0)

Step 3: ***Calculate the fuzzy total-relation matrix***

The fuzzy total-relation matrix may be generated in step 3 using the algorithm shown below:

$$Q = \lim_{k\to+\infty}(P^1 \oplus P^2 \oplus \ldots \oplus P^k).$$

The fuzzy total-relation matrix may be computed as follows if each element is written as $\tilde{t}_{ij} = (l''_{ij}, m''_{ij}, u''_{ij})$, it can be calculated as follows:

$$[l''_{fg}] = P_l \times (I - P_l)^{-1}.$$

$$[m''_{fg}] = P_m \times (I - P_m)^{-1}.$$

$$[u''_{fg}] = P_u \times (I - P_u)^{-1}.$$

It first determines the inverse of the normalised matrix in a sequential method for I4.0 social sustainability factors. This inverse then reduces the identity matrix (matrix I). The final step is to multiply the final matrix by the normalised matrix. **Table 6** displays the results of this mathematical process and the fuzzy DRM.

Table 9. Fuzzy total-relation matrix.

	Quality of life	Economic status	Government policies	Environmental conditions
Quality of life	(0.34,0.69,1.57)	(0.44,0.75,1.55)	(0.30,0.61,1.36)	(0.52,0.90,1.81)
Economic status	(0.66,1.09,2.02)	(0.30,0.64,1.46)	(0.40,0.75,1.55)	(0.60,1.03,1.99)
Government policies	(0.65,1.11,2.13)	(0.52,0.98,1.81)	(0.30,0.64,1.46)	(0.70,1.15,2.15)
Environmental conditions	(0.53,0.92,1.827)	(0.33,0.66,1.47)	(0.42,0.72,1.47)	(0.34,0.70,1.59)

Step 4: ***De-fuzzified into crisp values***

A firm value of the total-relation matrix was obtained using the CFCS approach suggested by Opricovic (2015) and Tzeng et al. (2014). The following are the steps of the CFCS method:

$$l_{fg}^{n} = \frac{\left(l_{fg}^{q} - \min l_{fg}^{q}\right)}{\Delta_{min}^{max}}$$

$$m_{ij}^{n} = \frac{(m_{fg}^{q} - min\, l_{fg}^{q})}{\Delta_{min}^{max}}$$

$$u_{ij}^{n} = \frac{(u_{fg}^{q} - min\, l_{fg}^{q})}{\Delta_{min}^{max}}$$

So that

$$\Delta_{min}^{max} = \max u_{fg}^{q} - \min l_{fg}^{q}.$$

Next, upper and lower bounds of normalised values are obtained.

$$l_{fg}^{s} = {m_{fg}^{n}} \Big/ {(1 + m_{fg}^{n} - l_{fg}^{n})}.$$

$$u_{fg}^{s} = {u_{fg}^{n}} \Big/ {(1 + u_{fg}^{n} - l_{fg}^{n})}.$$

The output of the CFCS algorithm is firm values.

The following **Table 7** presents the calculated total normalised firm values:

$$P_{fg} = \frac{[l_{fg}^{s}\left(1 - l_{fg}^{s}\right) + u_{fg}^{s} \times u_{fg}^{s}]}{[1 - l_{fg}^{s} + u_{fg}^{s}]}$$

Table 10. Crisp total-relation matrix.

	Quality of life	Economic status	Government policies	Environmental conditions
Quality of life	0.82	0.86	0.71	1.02
Economic status	1.18	0.76	0.84	1.14
Government policies	1.21	1.01	0.75	1.25
Environmental conditions	1.03	0.78	0.81	0.83

Step 5: ***Set the threshold value***

Matrix T's average values are used to create the relationship threshold. The network relationship map (NRM) is then displayed by ignoring incomplete relationships. The NRM only displays relationships with values in the matrix T above the threshold.

For matrix T, the threshold value setting is zero at starting, which further indicates that the specified causal relationship is not considered. We have kept this threshold value at 0.94, which simply means the causal relationship stated above is ignored by setting all values in the matrix T that are less than 0.94 to zero. The following **Table 11** presents the vital relationship model.

Table 11. Crisp total- relationships matrix by considering the threshold value.

	Quality of life	Economic status	Government policies	Environmental conditions
Quality of life	0.00	0.00	0.00	1.02
Economic status	1.18	0.00	0.00	1.14
Government policies	1.21	1.01	0.00	1.25
Environmental conditions	1.03	0.00	0.00	0.00

4. Results

In a matrix with depicted matrix elements, the above statement explains how to calculate the sums of rows (D) and columns (R). The sum of rows (D) and columns (R) is utilised to obtain the final results as follows:

$D = \sum_{f=1}^{n} Q_{fg.}$

$R = \sum_{f=1}^{n} Q_{fg.}$

In essence, these computations are used to determine the total number of rows (D) and the total number of columns (R) in a matrix, which may be helpful for several tasks, such as data processing and matrix-related mathematical operations. These sums may reveal essential patterns, traits, or attributes of the data or matrix under investigation. **Table 12** below shows the final output.

Table 12. Final priority order for I4.0 SSEs.

SSEs	Code	R	D	D+R	D-R
I4.0 green technology	SSE1	3.70	3.88	7.58	0.18
Employee economic status	SSE2	3.34	3.53	6.88	0.19
Social security concerns and employee well-being	SSE3	3.74	2.93	6.66	-0.81
Skills for I4.0 systems	SSE4	3.36	3.51	6.87	0.14
Eco-friendly supply chain initiatives	SSE5	2.84	3.15	5.99	0.30

Next, D+R and D-R are obtained, where D+R signifies the degree of importance of factor *i* in the entire system, and D-R signifies the net effects that factor *i* contributes to the system. The relationship between critical factors that enable social sustainability in I4.0 logistics is presented and covers RQ2.

4.1 Interpretation of Results

The horizontal line (D + R) indicates both the influence of the factors on the entire system and the influence of other system factors on the factor. As for the degree of importance, environmental conditions are evaluated first, while quality of life, government policies, and economic status are listed next. Economic status and government policies are the main factors in this study, while quality of life and environmental conditions are considered impacts. The vertical line (D-R) shows how much a factor impacts the system. The most important SSE identified is I4.0 Green Technology, which is in line with Vrchota et al. (2020) and Tseng et al. (2013). **Figure 3** shows the cause-and-effect diagram for I4.0 SSEs.

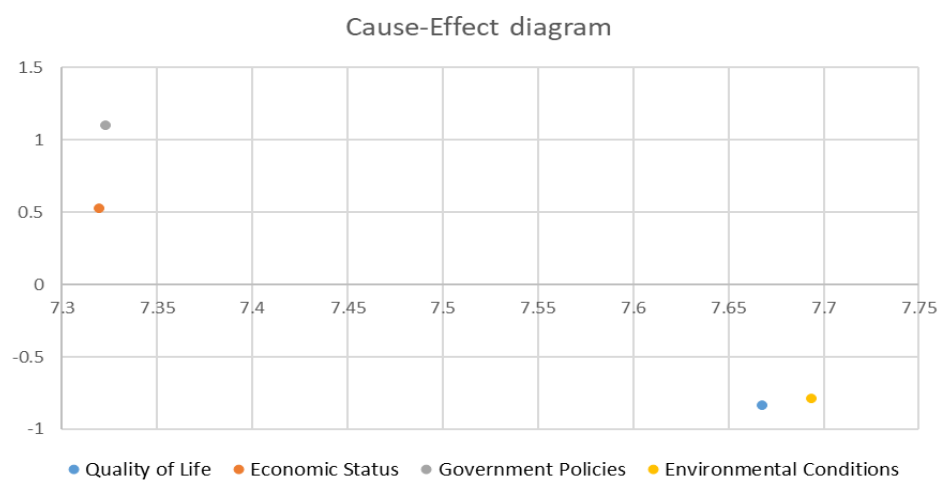

Figure 3. Cause and effect diagram for I4.0 SSEs (Source: authors).

5. Discussion

We examined social sustainability in engineering and technology-driven logistics operations. Jamkhaneh et al. (2022) point out that logistics is a key sustainability factor for modern companies. Green technologies, economic aspects, safety, competence and well-being proved to be essential factors. Managers need to think beyond adopting sustainable transportation methods, reducing carbon emissions, and optimising supply chain processes to minimise environmental impact. Green technologies represent renewable and energy-efficient systems and sustainable materials that reduce environmental impact and promote both health and well-being (Vrchota et al., 2020; Xu et al., 2023). Attah-Boakye et al. (2022) advocated considering the ecological footprint of multinational companies. The study's results focus on examining the economic empowerment of employees and their qualifications. It meets the needs of the hour. According to Rajput and Singh (2021), intelligent safety enabled by I4.0 can massively reduce workplace accidents, effectively improving the health and well-being of employees. For every nation, economic stability and growth form the basis of social sustainability. I4.0 models provide economic added value to effectively support social goals for large industries (Saniuk et al., 2022). The government can apply pressure to advance green supply chain management practices Ahmed et al. (2020). Social sustainability influences the operational performance of companies in many ways (Croom et al., 2018).

The role of engineering and technology is prominent. The mass adoption of I4.0 will help industries create secure jobs, add value to their lives, and even be profitable while addressing many other social issues. Future studies would include larger samples with diversified sources and evaluate how different technological solutions would contribute to better social sustainability. This study uncovered causal relationships related to social security issues and provided a systematic strategy for industrial decision-making. Industries must prioritise integrating I4.0 technologies to improve social sustainability in logistics operations. Social security and employee welfare policies should be strengthened to ensure the welfare of workers in the logistics industry. Policymakers and industry stakeholders could be inspired to develop programs to upskill the workforce in I4.0 technologies.

6. Conclusion

Social sustainability in engineering and technology-driven logistics operations is a crucial aspect. We began this research by examining the social sustainability factors in logistics in the I4.0 era and identifying the critical social sustainability factors that can help business decision-making. The result shows that introducing and implementing green technologies in the context of I4.0 is the most crucial aspect of sustainability. It clearly states that green practices will improve overall sustainability when accompanied by human moral approaches for better organizational and societal growth. Social sustainability is achieved when companies focus on the economic aspect, safety and well-being of the people involved in logistics operations, followed by green utility initiatives to support on-site operations. Achieving this requires minimising waste, reducing greenhouse gas emissions, and supporting ethical sourcing and manufacturing (Hussain et al., 2018). The study also concludes that employees' ability to deal with sustainable aspects of logistics plays an important role, similar to the argument of Passalacqua et al. (2024) on skilling operations persons. In order to study the influence of SSEs and important parameters for attaining social sustainability goals, the implementation aspect must take into account the stated preference while creating the working model of a particular industry. The various contributions of the study in the logistics sectors are as follows:

Theoretical contribution

The study helps identify not only the SSEs but also the significant factors that prevent the literature from being considered in this study. This study provides scientists with a background for further research as they gain insight into the responsible factors that enable social sustainability in logistics in the age of I4.0. The study also examines the causality of the social sustainability factors associated with I4.0 in logistics for battery decision-making. These results extend the existing body of literature by integrating fuzzy DEMATEL to identify and analyse the interrelations between social sustainability factors.

Practical contribution

The findings will enable logistics companies and supply chain operators to develop more effective strategies, help the business organisation meet sustainability requirements, and design systems that combine social sustainability with proven elements. The study helps derive specific mechanisms through which sustainable practices within the supply chain influence social security considerations, providing valuable insights for industries and policymakers alike.

Limitations and future research direction

In the future, a more detailed examination of the specific dimensions within I4.0 technologies could enable a deeper understanding of their impact on social security concerns. The nuanced interplay between economic status and I4.0 adoption, perhaps through longitudinal studies or cross-sectional analyses, would further contribute to the literature. The study captures the limited response from industry representatives to the survey, which could have been larger.

Conflicts of Interest

The authors confirm no conflicts of interest associated with this research. This study was carried out independently, without financial support, sponsorship, or funding from external agencies or organizations

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The author(s) declare that no assistance is taken from generative AI to write this article.

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