



Quantifying the Influencing Issues of Digital Integration with Supply Chain Using Graph Theory (GT)

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ABSTRACT

This study aims to develop a model that quantifies the key issues influencing digital integration within the supply chain (SC) as a single numerical value, termed the integrity index. This index value helps organisations in identifying and addressing various SC issues related to digital integration. The model calculates the integrity index by analysing the interactions among different issues involved in digital integration. The graph theoretic approach (GTA) technique is applied to examine the integrity index value by analysing the interactions among different issues involved in digital integration. In GTA, the various issues influencing the digital integration are identified, and a model with the help of a digraph is prepared based on their interdependencies. From this digraph, an adjacency matrix is created, and the permanent function of this matrix is computed to derive the integrity index. The integrity index is evaluated by using GTA in the context of Indian small and medium enterprises (SMEs). By using the GTA framework, the integrity index is also calculated in the best- and the worst-case scenarios. Findings from the study reveal that financial issues are the most influencing ones impacting digital integration, followed by organisational and technological issues, providing key focus areas for improvement.

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1. Introduction

The supply chain (SC) is considered as the backbone of any organisation's business. It starts from the process of getting raw material for the product from the manufacturer and finishes with the end consumer (Shukla et al., 2011). The SC involves the flow of material, money, and information. Supply chain management aims to maximize value and productivity while minimizing costs by fostering seamless cooperation among all supply chain agents. As new-age digital technology is emerging, organisations are focusing on their supply chains to be more efficient and faster to take the competitive advantage (P. Agrawal & Narain, 2018). Organisations have observed the criticality and value of digital technologies for their growth and their own businesses during the COVID-19 pandemic, and they are looking to digital integration with their SC. As digital integration drives the expansion and growth of the supply chain, they also introduce new complexities and obstacles (Jennings, 2023). Integrating technology is not just a click of a button. It requires the whole management's involvement, teamwork, and ideas that will emerge to better utilise systems in achieving business objectives. The integration of digital technology is driving significant transformations in supply chains and is now widely recognised as a key force behind innovation in organisational management. Digital inventions come from digital technologies and their qualities (Nowicka, 2019). Digital integration enables supply chain (SC) managers to prioritise the implementation of innovative processes, enhance corporate communication, and increase business agility (Gunasekaran et al., 2008). The COVID-19 pandemic exposed significant supply chain disruptions, highlighting the urgent need for digital integration to enhance resilience (Birkel et al., 2023), adaptability (Bani-Irshid et al., 2024), and overall supply chain performance (Spieske et al., 2023). Due to the rapidity of innovation in business, digital integration with SC is crucial for modern enterprises. Digital integration improves customer service, supplier connections, sales, and business growth (P. Agrawal et al., 2020). Digital integration signifies the digital transformation of the system with the help of newly developed digital technologies, such as artificial intelligence and robotics, the Internet of Things (IoT), 3D printing, cloud computing, advanced analytics, radio frequency identification (RFID), blockchain, augmented reality, and cloud technology (Cañas et al., 2021) to adapt and enhance company approaches, regulations, culture, and client experiences to meet changing business demands (Saarikko et al., 2020).

Implementing digital integration in the supply chain offers numerous advantages for firms across industries. However, it also involves operational and financial considerations that may impede sustained success in the long term (Zaman et al., 2023). However, this digital integration in the supply chain confronts some issues and challenges which need to be addressed for successful integration (Choudhury et al., 2021). The two primary impacts of digital integration in SC may be as follows: First, several obstacles hinder businesses from implementing SC-wide digitalisation plans, and second, the SC and businesses may find future use for the enabling components as they transition to digital technologies. In this transition phase of digitalisation, SC managers look forward to challenges as well as opportunities for themselves in digital transformation (V. K. Dixit et al., 2024). Since the research in the area of DSC is in its infancy stage, there are numerous significant opportunities to research in identifying issues, challenges, drivers, and enablers to digital integration with the system (Frederico et al., 2020). It has the potential to enhance SC performance by integrating digital technologies (R. Agrawal et al., 2023) into the DSC framework more effectively. Additionally, during the pandemic, COVID-19 supply chain disruption occurred across the world, and the small medium enterprises (SMEs) were most affected due to the pandemic and faced difficulty keeping business running smoothly. A need for the integration of technology with the supply chain is created to make the supply chain agile and sustainable (Chauhan et al., 2023). There are some major issues that arise at different levels during the digital integration with the supply chain in SMEs. However, limited research has addressed these issues which are influencing digital integration in SC of SMEs. This study fills that gap by providing a quantitative assessment of the key issues influencing digital integration in SMEs, emphasizing their interdependencies and offering valuable insights for supply chain managers. This study is carried out with the research question (RQ), i.e., "How can digital integration with the supply chain be evaluated as a numerical index by considering the interdependence of associated issues?" This quantification enables supply chain managers to assess and address issues related to digital integration. The Graph Theoretic Approach (GTA) method has been used to evaluate the integrity index for the case of Indian SMEs. In GTA, the various issues are categorised into four different

categories, and their interdependencies are modelled through the digraph. The digraph is further converted into an adjacency matrix whose permanent function value signifies the integrity index. The main objectives of this study are (i) to identify the various issues for digital integration with SC, (ii) to develop a mathematical model to measure the intensity of the issues using GTA, and (iii) to determine the integrity index to evaluate the impact of issues in digital integration.

2. Theoretical Background

Over the last few years, there has been a surge of studies examining DSCs and their consequences. These studies have shed light on many valuable insights. Many research investigations focus on the potential benefits of digitalisation adoption while ignoring some issues and important success criteria. Some issues, such as legal and ethical issues, need to be studied for a successful digital integration. This study has been done not only to identify the issues but also to quantify the influencing issues and prioritise them based on their relative intensity using GTA methodology. The issues associated with digital integration in supply chains can vary significantly depending on factors such as industry type, organizational size, and geographical location. In this study, a total of 18 key issues related to digital integration have been identified through a comprehensive review of existing literature and consultation with industry experts. Furthermore, they are classified into four major categorical issues: Organisational, Financial, Technological, and Legal and ethical issues, as shown in Table 1. Their description is provided in the following sections.

Table 1. Influencing Issues of Digital Integration with SCM

| S.N. | Category of issue | Influencing issues | References |
|------|--|--|--|
| 1 | Organisational Issue (R ₁) | Lack of top management commitment (R ₁₁) | De Vass et al. (2021), Horváth & Szabó (2019), Mishra (2015), Bughin et al. (2015) |
| | | Resistance to change (R ₁₂) | Kinitzki et al. (2019), J. Li et al. (2016), Khanzode et al. (2021) |
| | | Agile organisation structure (R ₁₃) | Jamwal & Agrawal (2019), Lindner & Leyh (2018), Kinitzki et al. (2019) |
| | | Lack of risk management practices (R ₁₄) | Zoghi (2017), de Araújo Lima et al. (2020), Rashid et al. (2024) |
| | | Lack of long-term planning (R ₁₅) | Gupta et al. (2022), Xu (2014), Wang et al. (2007) |
| 2 | Financial Issues (R ₂) | Cost of implementation (R ₂₁) | P. Agrawal et al. (2020), Buntz (2016), Nowicka (2019), Weerabahu et al. (2023) |
| | | Lack of investment in human capital (R ₂₂) | Liboni et al. (2019), Ruzzier et al. (2007), Sivathanu & Pillai (2018) |
| | | Scalability and flexibility costs (R ₂₃) | Büyüközkan & Göçer (2018), Küsters et al. (2017) |
| | | Lack of supply chain financing (R ₂₄) | Alora & Barua (2019), Chen et al. (2021), Küsters et al. (2017), |
| | | Macroeconomic fluctuation (R ₂₅) | Basu & Siems (2004), Clancy et al. (2024), Genberg (2020), Guo et al. (2016) |
| 3 | Technological Issues (R ₃) | Data integrity and accuracy with legacy systems (R ₃₁) | Choi & Luo (2019), De Vass et al. (2021), Ebunoluwa Johnson et al. (2024) |
| | | Lack of IT infrastructure (R ₃₂) | Buntz (2016), Raj et al. (2020), Schröder (2016) |
| | | Lack of trust between technological partners (R ₃₃) | Angeles (2009), Choi & Luo (2019), V. K. Dixit et al. (2024) |
| | | Cybersecurity risk (R ₃₄) | Kache & Seuring (2017), OECD (2021), Pan et al. (2021) |
| 4 | Legal & Ethical Issues (R ₄) | Intellectual property (R ₄₁) | Adu-Amankwa & Daly (2023), Buyya et al. (2013), Kitching & Blackburn (1998) |
| | | Jurisdictional issues (R ₄₂) | Azamat (2024), Buyya et al. (2013), Massimino et al. (2018) |
| | | Regulatory and compliance (R ₄₃) | Afrifah et al. (2022), Dasgupta et al. (2020), Kozma & Varga (2020) |
| | | Insider threads (R ₄₄) | Arampatzis (2023), Hammi et al. (2023), Hofmeier & Lechner (2021) |

2-1. Organisational Issues

2-1-1. Lack of Top Management Commitment: The lack of top management commitment and support is considered as one of the major issues in digital integration (Bughin et al., 2015). The successful digital integration needs establishing a clearly defined vision and strategy for the DSC transformation that aligns with the overall business objectives. Securing top officials' commitment and needful resource allocation is key to driving successful transformation. SMEs have comparatively lower flexibility and less support from top management (Horváth & Szabó, 2019). The dedication and support of top management indicate that administrators are actively involved throughout the entire process of creation and implementation, and they provide full backing for creative endeavours within the organisation (Mishra, 2015). The role of top management becomes more vital in the process to identify the opportunities from the new age digital technologies (De Vass et al., 2021).

2.1.2. Resistance to Change: Staff and management of an organisation might be resistant to changes in the organisation due to potential job displacement, fear of the unknown, fear of job loss or disruptions to established workflows (Khanzode et al., 2021). Continuous changes and updates to systems and processes can lead to change fatigue, reducing employee morale and productivity (Kinitzki et al., 2019). Employees accustomed to traditional methods may be hesitant to adopt new digital tools. Implementing and managing complex digital systems might require hiring personnel with specialised skills (J. Li et al., 2016). The employees need to adopt a new digital environment; otherwise, their poor digital skills and capabilities are considered a major issue for organisations that are aiming for rapid growth.

2.1.3. Lack of Agile Organisation Structure: Organisations should implement effective governance structures to oversee digital transformation, ensuring that clear decision-making processes and accountability mechanisms are in place (Jamwal & Agrawal, 2019). The organisational structure has a crucial role in digital transformation (Kinitzki et al., 2019). Digital supply chains face fast-changing demands from customers, technology, and market conditions. Agile structures allow firms to quickly adjust to these changes, allowing them to respond to new opportunities and challenges. The major challenge for the top managers is to design an organisational structure which is adaptive, responsive, flexible, accessible, and progressive (Lindner & Leyh, 2018).

2.1.4. Lack of Risk Management Practices: The lack of risk management practices in digital supply chains can lead to significant vulnerabilities. Without proper risk assessment, companies face increased threats from cyberattacks, data breaches, and system failures. Risk management practices are a process which identifies risk at various levels in business, such as strategic risk, supply risk, customer risk, asset impairment risk, competitive risk, reputation risk, financial risk (Israel et al., 2023), fiscal and regulatory risk, and legal risk (Zoghi, 2017). This can disrupt operations, cause financial losses, and damage reputations (de Araújo Lima et al., 2020). Effective risk management is essential to ensure resilience and security in digital supply chains (Rashid et al., 2024). Enterprise Risk Management (ERM) allows the company to achieve its strategic goals by detecting, analysing, evaluating, reducing, tracking, and managing any risk or possible threat to these goals.

2.1.5. Lack of Long-Term Planning: Lack of long-term planning hampers growth and adaptability, resulting in missed opportunities, inefficient resource allocation, and financial instability, ultimately threatening an organisation's future success and market competitiveness (Xu, 2014). Proper innovation strategies are required in long-term planning for longer-term sustainability (Cañas et al., 2020) in a digital environment. A strategic long-term planning plays a crucial role in successful digital integration (Gupta et al., 2022). Strategic long-term planning involves figuring out the organisation's desired outcomes in the future, creating a strategy to reach those outcomes, and deciding how to best allocate or redirect resources to make that happen (Wang et al., 2007).

2-2. Financial Issues

2.2.1. Cost of Implementation: Implementing new digital technologies like cloud platforms, analytics tools, or Internet of Things (IoT) sensors can be expensive. Maintaining and updating these systems requires ongoing investment in personnel and resources (Nowicka, 2019). Securing loans or investments for digital initiatives can be difficult for some companies. Integration of new digital systems with existing legacy systems could be complex and expensive, needing customisation and data migration. High upfront capital outlay and potential long payback periods can deter organisations,

particularly small and medium-sized enterprises (SMEs), from embracing digital supply chains despite the potential for long-term benefits (Weerabahu et al., 2023). The digital transformation has substantial implementation and operating expenses. It is also challenging to determine the true return on capital invested in the modern SC environment, as the ROI may not be immediately apparent (P. Agrawal et al., 2020). The payback period can be long, and organisations need to manage cash flow effectively during this period; however, digital supply chains can lead to long-term cost savings and efficiency gains.

2.2.2. Lack of Investment in Human Capital: Digital supply chains rely on technologies like machine learning (ML), artificial intelligence (AI), Internet of Things (IoT), and advanced analytics. Without a workforce skilled in these areas, companies cannot effectively implement or manage these systems (Liboni et al., 2019). By building a skilled, adaptable, and innovative workforce, companies can unleash the entire potential of digital supply chains, drive efficiency, reduce risk, and acquire a competitive advantage. An organisation needs to invest in the enhancement of skills and knowledge of their employees by giving proper training and education (Ruzzier et al., 2007). The diverse set of useful skills and knowledge gained by an employee over time is referred to as human capital. The success of digital integration in SC will depend on talent development as well in a competitive environment (Sivathanu & Pillai, 2018). Human capital, as one of the cores of value chain in building and expanding the organisation, is underpinned by ever-evolving technology.

2.2.3. Scalability and Flexibility Costs: As supply chain operations grow or change, digital technologies may need to be scaled or modified accordingly. This can involve additional expenses for system upgrades, expanding IT infrastructure, or customizing software solutions to accommodate evolving business needs (Küsters et al., 2017). Additionally, organisations are concerned about the return on their investment in digital integration adoption (Büyüközkan & Göçer, 2018). As the volume of data and transactions grows, the underlying infrastructure needs to be expanded. This includes hardware, software, and network capacity. Increased flexibility can introduce new risks, requiring investments in risk assessment and mitigation strategies.

2.2.4. Lack of Supply Chain Financing: Digital supply chain financing (DSCF) is a solution which helps businesses improve their cash flow and supply chain resilience through automation, transparency, and collaboration. The issue of SCF is majorly concerned with SMEs due to regulatory requirements, lack of SC visibility, and risk of fraud (Küsters et al., 2017). Lack of supply chain financing limits SMEs' ability to maintain inventory, meet demand, and invest in growth. Without access to affordable credit or financial support, these businesses struggle with cash flow, leading to delays, missed opportunities, and weakened competitiveness within the supply chain ecosystem (Alora & Barua, 2019). Compared to multinationals and large enterprises, SMEs are disproportionately more affected by denied applications because of their limited scale of business and poor credit rating (Chen et al., 2021). The trade financing gap contributes to disparities and weakened supply chains.

2.2.5. Macroeconomic Fluctuation: Macroeconomic fluctuations, such as inflation, currency volatility, inflation and monetary policies, are considered a significant issue in implementing digital supply chains (Genberg, 2020). Macroeconomic fluctuations increase uncertainty in costs and risks, disrupting supply chain operations. This unpredictability might result in restructuring, inefficiencies, and instability, ultimately weakening the overall supply chain network (Clancy et al., 2024). Rising inflation increases the cost of technology, software, and services, while currency fluctuations make international procurement unpredictable. Higher interest rates raise borrowing costs, discouraging investment in digital infrastructure (Guo et al., 2016). Economic downturns reduce consumer demand, shrinking company revenues and limiting funds for digital initiatives (Basu & Siems, 2004). Additionally, regulatory changes and global trade disruptions add uncertainty and increase costs. To navigate these barriers, businesses need to adopt flexible budgeting, risk management strategies, and incremental implementation to mitigate the financial impact of macroeconomic shifts.

2-3. Technological Issues

2.3.1. Data Integrity and Accuracy with Legacy Systems: Digital supply chains require integration between different systems and technologies. Most organisations depend on legacy systems that were not built to cope with modern data integration requirements. It may be difficult to integrate these systems, particularly when they utilise distinct protocols and data formats (Ebunoluwa Johnson et al.,

2024). The credibility of data acquired from multiple sources needs to be checked as well (Choi & Luo, 2019). For successful digital integration, data becomes a valuable asset for the organisation. Poor data quality may impact the data integrity, and it will be difficult to develop a platform that manages SC activities (Xu, 2014). Companies need to ensure that their systems can communicate with one another seamlessly. They also need to ensure that their suppliers and partners have the necessary integration capabilities.

2.3.2. Lack of IT Infrastructure: Lack of good IT infrastructure creates a challenge of data management in the DSC. Every member of DSC needs to be integrated with the system for successful digital integration; therefore, a good IT infrastructure needs to be built. A good IT infrastructure provides data security and enhances the trust between the partners (Raj et al., 2020). Buntz et al. (2016) mentioned in his study that 33% of people believe the lack of IT infrastructure is an issue in the adoption of digital technology. The massive data is generated in DSC processes, and the management of this massive data is critical. An organisation needs to ensure the data is accurate and timely accessible to all stakeholders. Companies located in rural areas face the internet connectivity issue due to poor IT infrastructure. For real-time data monitoring, information sharing, and data accessibility, there is a need to raise the fibre optic and 5G coverage to unlock the potential of digital integration (Schröder, 2016).

2.3.3. Lack of Trust between Technological Partners: Manufacturers frequently work together with a number of third-party vendors, suppliers, and stakeholders across their supply chains. However, this partnership could lead to vulnerabilities and threats as third-party security practices and data handling capabilities may not meet the manufacturer's standards. This imbalance might lead to data leaks or unauthorised access (V. K. Dixit et al., 2024). To prevent these risks, manufacturers must thoroughly examine and monitor their third-party partners' security postures, develop secure data transmission methods, and enforce stringent contractual data protection responsibilities. One of the major issues in information-sharing policies is creating trust because companies are always protective of their data and reluctant to share it (Angeles, 2009). Once a company shares data with suppliers, it loses full control over how that data is handled. To safeguard against potential risks, contracts should clearly shift the responsibility for data security to the supplier, using tailored indemnification clauses that hold them accountable for any breaches or non-compliance (Choi & Luo, 2019).

2.3.4. Cybersecurity Risk: The cybersecurity threat is one of the most significant issues facing the digital supply chain. As supply chains become increasingly interconnected and reliant on digital technologies, the threat of cyberattacks rises. Hackers may extract important information, interrupt business operations, gain customers' sensitive data (Kache & Seuring, 2017), and cause significant financial losses. In digital integration, cybersecurity is a major issue, as data may be leaked or transferred to rival or third parties. Cybersecurity risks generate a fear of information sharing among the stakeholders as organisations become more careful about data sharing (Pan et al., 2021). Accordingly, companies need to implement robust cybersecurity processes and deploy a strong IT infrastructure and network systems as measures to protect their digital supply chains by preventing unauthorised access of sensitive data and computer systems and networks (OECD, 2021).

2-4. Legal and Ethical Issues

2.4.1. Intellectual Property: The transition from regional to global supply chains has resulted in massive diffusion of intellectual property and proprietary information throughout enterprises' extensive networks of partners and activities. SMEs are also generally considered as innovators in the economy, and promoters keep the information confidential as trade secrets. When combined with the rise of digitisation and the growing use of internet-enabled technologies, these trends have significantly increased the number of potential attack points for malicious actors, and it becomes necessary to protect the intellectual property rights through formal legal ways (Kitching & Blackburn, 1998). Succinctly stated, supply chains are vulnerable to intellectual property theft. Adu-Amankwa and Daly (2023) considered the IP security issue of adaptive manufacturing/3D printing in DSC. The organisations are using services of third parties providing software as a service (SaaS). It becomes important for a service provider not only to keep safe the data from external entities but also to ensure the IP attached to the data (Buyya et al., 2013).

2.4.2. Jurisdictional Issues: Jurisdictional issues arise mostly from the geographical origin of data and particular legal frameworks that govern that region. Increasing virtualisation of economic activities has also introduced complex jurisdictional and regulatory challenges stemming from the intrinsic borderless nature of cyberspace (Buyya et al., 2013). Issues arise because different countries have different laws for data protection. Since digital assets can be easily transferred across borders, they often cross into multiple legal jurisdictions, which complicates matters (Massimino et al., 2018). This creates what's known as a conflict of laws, where different countries' regulations may contradict one another, even on the same topic. Subcontracting can also cause jurisdictional challenges, as sharing digital assets across borders involves different legal rules and cultural practices, making it harder to maintain confidentiality and ensure proper data handling (Azamat, 2024).

2.4.3. Regulatory and Compliance: Digital supply chains must abide by legislation pertaining to privacy and data protection. Organisations must make sure they follow these rules to avoid getting into legal trouble or facing fines (Afrifah et al., 2022). Moreover, they have to ensure that their partners and stakeholders are abiding by these rules and regulations. The government regulates the digital technology for security purpose and the companies need to fulfil the regulatory and compliance laws. Regulatory and compliance risks in digital supply chains arise from evolving laws and regulations governing data protection, cybersecurity, trade, and labour standards. As supply chains become more digitized, companies must adhere to international data privacy laws, such as general data protection regulation (GDPR) (Dasgupta et al., 2020). Digital supply chains often operate across different countries and continents. Because of this, it's important to make sure they follow the laws in every location they operate in to stay legally compliant (Kozma & Varga, 2020).

2.4.4. Insider Threats: Insider threats in digital supply chains refer to risks posed by employees, contractors, or other trusted individuals who have access to sensitive data or systems. These insiders can intentionally or unintentionally compromise security by leaking proprietary information, misusing data, or introducing vulnerabilities into the system (Arampatzis, 2023). In digital supply chains, where information is shared across multiple partners and regions, insider threats are particularly dangerous as they can lead to data breaches, intellectual property theft, or disruptions in operations (Hofmeier & Lechner, 2021). Ensuring strong access controls, monitoring, and training can help mitigate these risks. Insider threats in digital supply chains pose ethical issues by enabling unauthorised access or misuse of sensitive data, leading to breaches, financial loss, and compromised trust in supply chain integrity (Hammi et al., 2023). Frequent training and awareness initiatives can also aid in informing staff members about their obligations and roles in data security.

3. Research Methodology

A logical and systematic approach, called the Graph Theoretic Approach (GTA), is developed with combinatorial mathematics (Geetha & Sekar, 2016). It is a powerful tool that analyses the system and subsystems and gives a numerical score value for the whole system. In this method, various digraphs are developed to show the interactions among the various factors of the system and subsystems in the form of nodes, representing factors, and edges, representing their inter-relationship. Pairwise comparison matrices are developed from the digraph for computation purpose and their elements represent all the factors and their relative importance (S. Dixit & Raj, 2019). Permanent of the matrix is calculated to characterise a system. Various researchers have used this methodology for their research studies in various areas of science and technology. Singh and Singru (2018) applied GTA to understand complex manufacturing structures and analyse lean initiatives. Aravind Raj et al.'s (2013) comprehensive agility index is estimated for modelling the agile system. A framework for outsourcing decisions in reverse logistics is developed and analysed by outsourcing index, estimated by a graph theoretic approach (S. Agrawal et al., 2016).

3-1. Digraph Representation

A digraph is a graphical representation of interdependencies of factors in terms of nodes and edges. It consists of nodes showing factors and edges showing interdependencies among the factors. The four major categories of issues $\{R_i\}$, where $i = 1, 2, 3, 4$, are represented by nodes, while the directed edges from node i to node j , that is $\{r_{ij}\}$, indicate the degree of relative importance of node i -th to node j -th. The digraph has 4 nodes representing major categories of issues: Organisational Issues (R_1), Financial

Issues (R_2), Technological Issues (R_3), and Legal and Ethical Issues (R_4), as shown in figure 1. Inter-relationship among major issues is shown by the directed edges. Each major category of issue consists of a number of categorical issues as shown in table 1. Similarly, the digraph for these issues from each category is also developed as shown in figures 2, 3, 4, and 5.

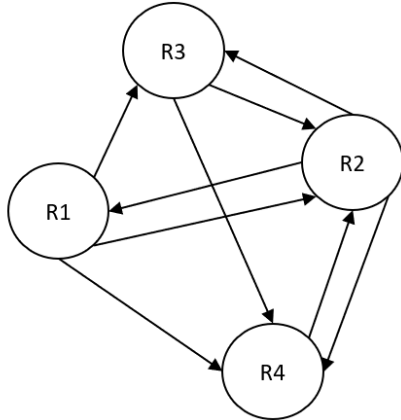


Fig. 1. Digraph of Major Category Issues

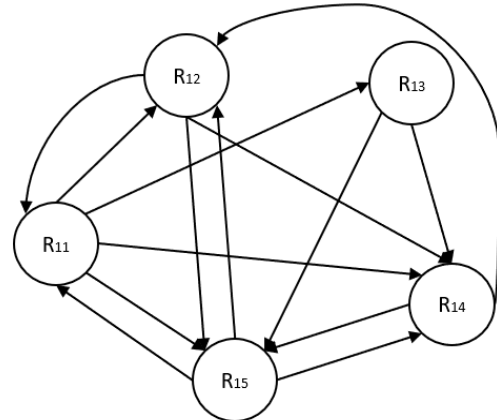


Fig. 2. Digraph for Organisational Issue

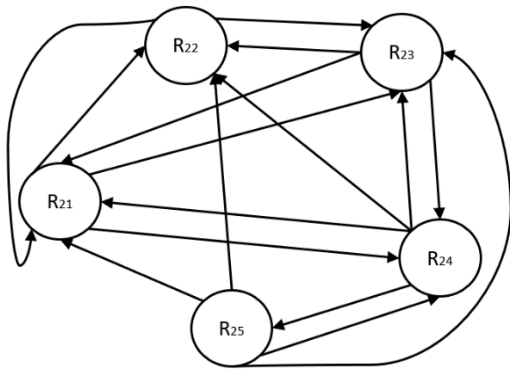


Fig. 3. Digraph for Financial Issues

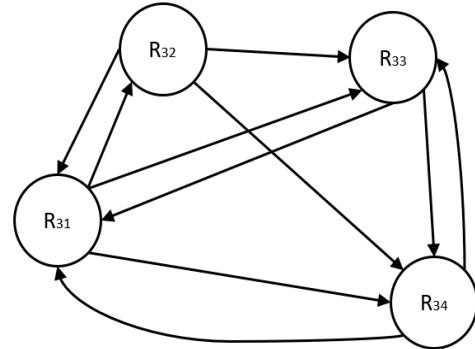


Fig. 4. Digraph for Technological Issues

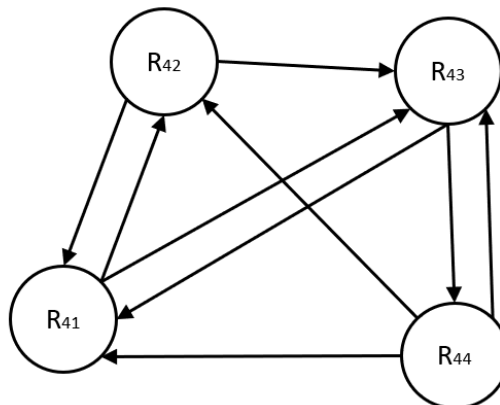


Fig. 5. Digraph for Legal and Ethical Issues

3-2. Matrix Representation

A digraph provides a graphical indication of the interdependencies of the factors. To calculate the integrity index and to analyse the mechanisms for our study, a digraph will be represented in a matrix form for computation convenience. The matrix $R = [r_{ij}]$, given by equation 1, is developed from the digraph. The matrix element $[r_{ij}]$ shows the relative importance of the i -th factor over the j -th factor. The diagonal elements are independent. The term R_i represents concerned issue inheritance. Fourteen experts from industry and academia were consulted for the data collection. All the experts are selected

based on their experience, qualification, and position. They had more than 10 years of experience in industrial operations and supply chain. All the experts are well qualified with minimum graduation degrees and are working at a managerial level. Inheritance values are collected on a 1–9 scale, and inter-dependencies values are collected on a scale of 1–5, as shown in Table 2.

Table 2. Inheritance and Inter-Dependence Measure

| Inheritance Measure | Assigned weight | Interdependencies Measure | Assigned weight |
|---------------------|-----------------|---------------------------|-----------------|
| Extremely low | 1 | Very weak | 1 |
| Low | 2 | Weak | 2 |
| Moderately Low | 3 | Medium | 3 |
| Below Average | 4 | Strong | 4 |
| Average | 5 | Very Strong | 5 |
| Above Average | 6 | | |
| Moderately High | 7 | | |
| High | 8 | | |
| Extremely High | 9 | | |

3-3. Analysis of Permanent Function Value

The permanent function matrix (PFM) is shown by equation 2, and it contains interdependency values as off-diagonal elements for all four major categories of issues, i.e., Organisational Issues (R_1), Financial Issues (R_2), Technological Issues (R_3), and Legal and Ethical Issues (R_4). Here, the values of diagonal elements represent inheritance and will be evaluated from the permanent functions value $\{R_i^* = per(R_i)\}$ of the sub-attribute’s matrices. Permanent function value is determined in the same manner as the determinant of a matrix is calculated. The only difference is that the negative signs are omitted and only positive signs are taken during the calculation of the permanent function value.

$$R = \begin{bmatrix} per(R_1) & r_{12} & r_{13} & r_{14} \\ r_{21} & per(R_2) & r_{23} & r_{24} \\ r_{31} & r_{32} & per(R_3) & r_{34} \\ r_{41} & r_{42} & r_{43} & per(R_4) \end{bmatrix} \tag{1}$$

$$R = \begin{bmatrix} R_1^* & 4 & 5 & 2 \\ 4 & R_2^* & 4 & 1 \\ 0 & 3 & R_3^* & 3 \\ 0 & 2 & 0 & R_4^* \end{bmatrix} \tag{2}$$

Similarly, the matrices derived from the diagraphs for Organisational Issues (R_1), Financial Issues (R_2), Technological Issues (R_3), and Legal and Ethical Issues (R_4) are presented in equations 3, 4, 5, and 6, respectively. The permanent (R_i) of each category of issues is also calculated from the matrix, as represented in equations 3, 4, 5, and 6. These matrices serve as the foundation for further quantitative analysis, including the calculation of permanent function values, which help identify the intensity and influence of each category (Geetha & Sekar, 2016). The term $per(R_i)$ represents concerned issue inheritance and is calculated as a permanent function value from the matrices given in equations 3, 4, 5, and 6 for organisational, financial, technological, and legal and ethical issues, respectively.

$$R_1 = \begin{bmatrix} 9 & 8 & 6 & 7 & 7 \\ 7 & 7 & 0 & 5 & 4 \\ 0 & 0 & 4 & 7 & 5 \\ 0 & 5 & 0 & 5 & 7 \\ 3 & 6 & 0 & 6 & 4 \end{bmatrix} \tag{3}$$

$$R_2 = \begin{bmatrix} 8 & 7 & 8 & 6 & 0 \\ 5 & 7 & 7 & 0 & 0 \\ 6 & 4 & 4 & 0 & 0 \\ 8 & 6 & 6 & 8 & 4 \\ 4 & 2 & 6 & 7 & 5 \end{bmatrix} \quad (4)$$

$$R_3 = \begin{bmatrix} 6 & 6 & 7 & 5 \\ 8 & 7 & 6 & 9 \\ 4 & 6 & 7 & 0 \\ 7 & 0 & 7 & 8 \end{bmatrix} \quad (5)$$

$$R_4 = \begin{bmatrix} 6 & 3 & 5 & 0 \\ 6 & 5 & 7 & 0 \\ 7 & 0 & 7 & 5 \\ 6 & 7 & 4 & 7 \end{bmatrix} \quad (6)$$

Permanent function values R_1^* , R_2^* , R_3^* , and R_4^* are calculated from the matrices shown in equations 3, 4, 5, and 6, respectively, and their values are as follows: $R_1^* = \text{Per}(R_1) = 134262$, $R_2^* = \text{per}(R_2) = 146744$, $R_3^* = \text{per}(R_3) = 26883$, and $R_4^* = \text{per}(R_4) = 9466$. These permanent function values of individual issues are diagonal values in matrix represented by equation 2, while the new matrix is represented by equation 7. Now the Permanent value (R^*) for this matrix is calculated.

$$R = \begin{bmatrix} 134262 & 4 & 5 & 2 \\ 4 & 146744 & 4 & 1 \\ 0 & 3 & 26883 & 3 \\ 0 & 2 & 0 & 9466 \end{bmatrix} \quad (7)$$

The permanent of matrix, i.e., $\text{Per}(R) = R^* = 5.01369 \times 10^{18}$, given in equation 7, is named as integrity index, which indicates how intensely issues are arising when integrating digital technologies into the organisation's supply chain.

3-4. Range of Integrity Index

The approach described above is effective for evaluating certain organisation's capabilities to address the issues for digital integration employing a permanent function value, i.e., integrity index. There will be a best scenario (minimum index value) and a worst scenario (maximum index value) which help an organisation to discover how far they are from achieving the best case and what possible improvement can be implemented to achieve the best level. The maximum value of the integrity index is calculated by putting the maximum value 9 in the matrices of each category of issues given in equations 3, 4, 5, and 6, and the permanent function value is again determined in the same manner. Similarly, the minimum value of the integrity index is calculated by putting the minimum value 1 in the matrices of each major category of issues, and the permanent function value is again determined in the same manner. All the maximum and minimum values are compiled and listed out in Table 3.

Table 3. Maximum and Minimum Value of Integrity Index

| Issues | Maximum value | Maximum logarithmic value log10 | Minimum value | Minimum logarithmic value log10 | Current value | logarithmic value log10 |
|-------------------|--------------------------|---------------------------------|--------------------------|---------------------------------|--------------------------|-------------------------|
| per (R_1) | 403794 | 5.61 | 36066 | 4.56 | 134262 | 5.13 |
| per (R_2) | 362386 | 5.56 | 29218 | 4.47 | 146744 | 5.17 |
| per (R_3) | 37950 | 4.58 | 8622 | 3.94 | 26883 | 4.43 |
| per (R_4) | 19392 | 4.29 | 2656 | 3.42 | 9466 | 3.98 |
| Per (R) | | | | | | |
| {Integrity Index} | 1.07688×10^{20} | 20.03 | 2.41315×10^{16} | 16.38 | 5.01369×10^{18} | 18.70 |

4. Result and Discussion

This investigation evaluates various categories of issues, and the permanent function values and their range for each category of issues in digital integration with SC of SMEs were determined. The permanent values for each category issue are converted to log scale for the simple interpretation of the results, as shown in Table 2, and the radar diagram is presented in Figure 6, indicating the intensity of issues. Using GTA analysis, the overall intensity of major issues is quantified into a single numerical value, that is the integrity index calculated, i.e., 5.01369×10^{18} , and its corresponding logarithm value is 18.70. If the difference between the integrity index value and its best value (i.e., minimum value) is lower than the difference between the integrity index value and the worst value (i.e., maximum value), then the integrity index has closeness to the best value. It signifies that the organisation has less impact on the issues (Lingkon et al., 2025) in digital integration, is in much good condition for digital integration, and is capable of addressing issues in an effective manner. The higher difference indicates the higher intensity of issue, i.e., closeness to the worst value. It signifies that the issues have higher intensity for influencing the digital integration and the organisation needs to focus on mitigating the issues. In the current study, the integrity index value is close to the maximum value, signifying an overall strong intensity of issues towards digital integration in SC of SMEs.

It is evident from the above study that the financial and organisational issues have a high intensity with the permanent function values of 146744 and 134262, respectively. The above study results are in line with the study carried by Raj et al. (2020) which suggest that the lack of top management, financial constraints, and the lack of long-term planning are the most significant issues in DSC implementation. Financial issues, the cost of implementation and investment in human capital, are major concerns, arising due to lack of funds (D. Li et al., 2019). This study reveals that SMEs need more focus to mitigate financial and organisational issues in digital integration.

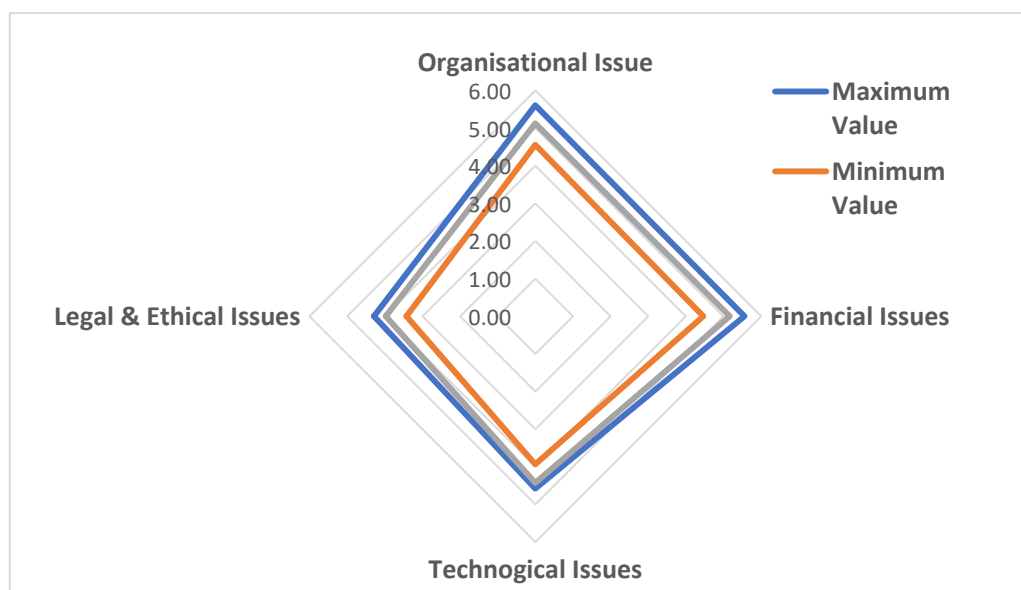


Fig. 6. RADAR Diagram for the Intensity of Issues

Although high initial capital may be required in the implementation of digital integration with the supply chain, this digital integration can help to improve the performance of the organisation and to connect with the world. Moreover, training and education of employees need to be done on a periodic basis to build human capital and to change the status quo of the employees.

Technological issues, having a permanent function value of 26883, come at the third highest intensity of issues. It includes data integrity with the legacy system, cybersecurity, and the lack of trust between technological partners due to fear of information loss. Existing data may be fragmented across different systems, making it difficult to integrate with new digital tools. Integrating data from various sources, including legacy systems, can be expensive and time-consuming. Security breaches and data leaks can be a major concern when integrating digital systems across the supply chain. A

good IT infrastructure is required as connectivity across the supply chain may be an issue, particularly for remote locations.

Legal and Ethical Issues, having a permanent function value of 9466, comes at the last place. They include intellectual property, jurisdiction, regulatory and compliance issues, and insider threats. Data privacy regulations and industry-specific compliance requirements can add complexity. A digital supply chain connects the organisations across different locations, and jurisdictional issues are mostly related to the location of data and the specific laws that apply in that location. As data and information can easily flow in a digital system, some data breaches and information may leak outside the system from insiders of the system. Regular training and awareness programs can also help educate employees about their roles and responsibilities in safeguarding data. New age technologies enable digital integration with the system and develop an ethical and sustainable operation in the system (Kumar et al., 2020). As companies adopt technologies like AI, machine learning, and automation in their supply chain operations, it is important to use them in an ethical way. Since these companies often operate globally, they face different cultural, legal, and regulatory challenges that can affect how they meet ethical standards. To stay compliant, businesses need to adjust their practices based on the laws and customs of each location they operate in. It is also vital that they communicate and collaborate effectively with their partners to ensure the ethical use of technology across the entire supply chain.

5. Conclusion, Limitations, and Scope for Future Work

In conclusion, the digital supply chain comes with its own set of issues. Companies need to address these issues to ensure that their supply chains remain efficient, secure, and resilient. Within the framework of graph theory, this study identifies and describes the key issues influencing digital integration in supply chains, subsequently constructing a digraph that visually represents the interdependencies among these issues. This digraph serves as the foundation for an adjacency matrix, a mathematical representation of the network's structure, from which the permanent function value is calculated, and this permanent value provides a measure for the overall impact of the issues of digital integration within the supply chain. A comparative intensity of major issues in digital integration within the supply chain has been examined. These major issues in digital integration for the SMEs are prioritised as follows: Financial, Organisational, Technological, and Legal and Ethical Issues. The findings of this study offer valuable insights for industrialists, practitioners, and researchers. Its main contribution is to guide SMEs toward successful digital integration by addressing key challenges strategically. A unique aspect of this research is the development of a mathematical model that helps in understanding and prioritising these challenges. By assessing the intensity of each issue, managers can focus their efforts more effectively and develop targeted strategies. Additionally, the model enables self-assessment by calculating the permanent function value for each category of issue, helping organisations identify and address internal gaps. These results are especially useful for those aiming to transition from a traditional to a smart supply chain. This methodology enables managers, industrialists, and practitioners to compare the intensity of major issues and create an Integrity Index for their organisations. By investing in cybersecurity, data management, integration, talent acquisition, automation, and regulation compliance, companies can overcome these issues and thrive in the digital age. Digital integration is a successful strategy for improving supply chain efficiency and effectiveness.

The study area of digital supply chains is a highly vast and emerging domain of research. Hence, this study has some limitations. Simultaneously identifying and analysing all potential major issues can be time-consuming and error-prone. In addition, the GTA technique relies on expert contributions to conduct all computations; any errors in recording and analysing responses result in wrong findings. It is critical to conduct data collecting and evaluation thoroughly. The major issues in digital integration can also be analysed with other methodologies. A Structural Equation Modelling (SEM) analysis can also be considered to identify and establish a relationship among the major issues in future studies.

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