Integrated analytical hierarchy process and grey relational analysis approach to measure supply chain complexity

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Purpose – The purpose of this paper is to understand the drivers that create complexity in the supply chain and develop a mathematical model to measure the level of supply chain complexity (SCC).

Design/Methodology/Approach of the paper – Through extensive literature review, we discussed various drivers of SCC. These drivers were classified into five dimensions based on expert opinion. Moreover, a novel hybrid mathematical model was developed by integrating analytical hierarchy process (AHP) and grey relational analysis (GRA) methods to measure the level of SCC. A case study was conducted to demonstrate the applicability of the developed model and analyze the SCC level of the company in the study.

Findings – We identified twenty-two drivers of SCC, which were further clustered into five complexity dimensions. The application of the developed model to the company in the case study showed that the SCC level of the company was 0.44, signifying that there was a considerable scope of improvement in terms of minimizing complexity. The company that serves as the focus of this case study mainly needs improvement in tackling issues concerning government regulation, internal communication and information sharing, and company culture.

Originality/Value – In this paper, we propose a model by integrating AHP and GRA methods that can measure the SCC level based on various complexity drivers. The combination of such methods, considering their ability to convert the inheritance and interdependence of drivers into a single mathematical model, is preferred over other techniques. To the best of the authors' knowledge, this is the first attempt at developing a hybrid multicriteria decision-based model to quantify SCC.

Keywords – Supply chain complexity, Complexity drivers, Complexity level, Analytical hierarchy process, Grey relational analysis, Case study

Paper type – Research paper

1. Introduction

A supply chain (SC) is a complex system in which different entities, processes, and resources interact with one another (Cheng et al., 2014). Today's SC is getting more complex due to the advent of globalization, customization, innovation, flexibility, and sustainability (Blome et al., 2014). Increasing complexity in the SC is a major obstacle in achieving organizational goals and improving customer satisfaction (Chand et al., 2020). Choi et al. (2001) emphasized the need to understand the complexity of a system so as to manage system behavior and improve performance. Complexity creates uncertainties and disruptions to the SC that result in increased cost with lower customer response (Gunasekaran et al., 2015). Such an analysis justifies the necessity of considering supply chain complexity (SCC) as an integral part of SC management. In literature, SCC is defined in various ways depending on the factors/dimensions that determine the degree of complexity (Aitken et al., 2016). Bozrath et al. (2009) defined SCC as the unpredictability of a system's response to a given set of inputs, whereas Isik (2010) described SCC as the quantitative differences between the predicted and real values. De Leeuw et al. (2013) described it based on variability, diversity, visibility, and uncertainty related to the SC. Christopher and Holweg (2017) established SCC as a condition of interconnectedness and interdependencies across a network, where a change in one element can affect other elements. It should be noted that SCC itself is not harmful to the success of an organization, but it should be considered a challenge, which, if managed successfully, might create opportunities to improve overall SC performance (Lee and Lee, 2007; Eckstein et al., 2015).

Various researchers have classified SCC into different types based on its nature. According to Serdarasan (2013), SCC can be static or structural, dynamic or operational, and decision-making. Static or structural complexity is identified based on the SC structure (Hamta et al., 2018), whereas dynamic or operational complexity highlights the process uncertainties in the SC (Wei et al., 2018). Decision-making complexity evolves from the characteristics of both static or structural and dynamic or operational complexities (Serdarasan, 2013). Flynn and Flynn (1999) and Bode and Wagner (2015) categorized complexity based on the locations, which may occur at the upstream, midstream, or downstream levels of the SC. Calinescu et al. (2001) categorized SCC into three types: decision-making, structural, and behavioral. Piya et al. (2017) classified SCC based on the level of management in the hierarchy that needs to take action to address it. The complexity that arises at the operational level, such as production planning, needs to be addressed at the tactical level. On the other hand, the complexity that arises because of the organizational structure needs attention at the strategic level.

According to Drzymalski (2015), identifying and measuring the SCC level is essential to manage complexity efficiently and gain a competitive advantage. It means that before managing complexity, it is necessary to identify the factors or drivers of complexity (Kavilal et al., 2017). Manuj and Sahin (2011) defined a complexity driver as an element that affects the structure and scope of the SC. Therefore, identifying the drivers that create complexity and then measuring the level of SCC are fundamental to managing complexity in the SC (Piya et al., 2019). The outcomes from such measurements offer quantitative information about the system that contributes to eliminating/minimizing SCC in general. Some researchers (Frizelle and Woodcock, 1995; Deshmukh et al., 1998; Sivadasan et al., 2002) have developed entropy-based mathematical models to measure complexity primarily related to the manufacturing process. Choi and Krause (2006) proposed a conceptual framework of the measure of complexity at the supply side as a function of the number of suppliers, their differentiation, and their level of interrelationship. Isik (2010) and Allensian et al. (2010) extended an initial entropy-based model to include multiple SC partners. De Leeuw et al. (2013) discussed a methodology to measure SCC in distributive trade based on eight SCC drivers. Further, Drzymalski (2015) developed a measure of SCC by incorporating virtual arcs. In this paper, a model was formulated by combining SC strength and SC clustering based on information, cost, distance, and denseness or connectivity of the network. According to Serdarasan (2013), many drivers push the SC toward complexity. Therefore, developing a model for measuring the SCC level without considering the effect of all drivers will not be comprehensive. From the literature analysis, it is noted that so far no model has been developed to quantify the SCC level based on the various drivers responsible for SCC. To fill such a research gap, in this paper we have identified the following two research questions:

RQ1. What are the significant drivers of SCC, and how do the SCC drivers represent the dimensions of complexity?

RQ2. How can the interdependencies between the SCC drivers be formulated to quantify the complexity level in the SC as a single numerical value?

From the consequences, the objective of this research was to develop a novel method to measure the complexity level in the SC by considering various SCC drivers. To accomplish the objective, the research proposed a mathematical model based on a multicriteria decision approach. To the best of the authors' knowledge, this is the first attempt at developing a model to quantify the SCC level based on a hybrid multicriteria decision approach. The remaining portion of the paper is structured as follows: Section 2 examines the SCC drivers based on the literature review and the association of these drivers with SCC. Section 3 discusses the classification of the SCC drivers into various dimensions. Section 4 presents the novel model developed to calculate the SCC level. Section 5 enumerates the application of the proposed method, sensitivity analysis, and insights drawn from the result based on the case study. Section 6 is dedicated to the implications and limitations of this research. Finally, the paper concludes with future research directions in Section 7.

2. SCC Drivers

Extensive literature was reviewed to understand SCC drivers. The literature was searched using bibliographic databases such as Science Direct, Scopus, Emerald, Springer, Google Scholar, and ISI Web of Science. To search the literature, the keyword combinations "supply chain complexity," "complexity driver," "complexity factors," and "manufacturing/production complexity" were used. It was found that past literature studied SCC either from the system-level or business unit (BU) point of view (Choi and Krause, 2006; Bozarth et al., 2009; Turner et al., 2018). Accordingly, drivers of complexity may lie within a BU or at the system level. To manage and add value to the entire SC network, a manager should acquaint themselves with the drivers at both the BU and system level, which creates complexity. This study presents the generic drivers of SCC at both the system level and BU, as shown below.

- *Product variety*: Having a variety of product portfolios is a business strategy in which companies achieve a competitive advantage through high customer satisfaction. However, adopting this business model leads to the involvement of more SC partners, which results in added complexity to the management of the SC (Jacobs and Swink, 2011; Lampón et al., 2017). In addition, having a variety of products necessitates a large number of product components and extensive interactions among these components. This, in turn, requires companies to maintain an inventory and other logistics support for multiple products (Shou et al., 2017).

- *Manufacturing process*: The different types and nature of manufacturing processes involve various factors and variables such as human resources, machine tools, and techniques to develop a product or service. Such an increasing number of factors and variables requires a high level of coordination and monitoring that often creates complexity (Flynn and Flynn, 1999; Perona and Miragliotta, 2004). Therefore, having a robust, flexible, and state-of-the-art manufacturing process and facility leads to less complexity in the product developmental process.

- *Internal communication and information sharing*: To achieve a competitive advantage in the marketplace, companies need to establish an up-to-date communication and information infrastructure (Shamsuzzoha and Helo, 2011; Piya et al., 2020). Effective communication and trust within various entities of an organization are essential for its smooth functioning. Chaos and distorted information caused by the incompatibility of available technology lead to friction, thereby creating complexity.

- *Planning and scheduling*: Inefficient planning and work schedules lead to operational complexity, delivery delays, and increased production costs (Isik, 2010; Bode and Wagner, 2015; Piya, 2019). The constant change in the production plan and inability of the company to adhere to worked-out schedules result in reduced operational performance.

- *Resource constraint*: Sufficient and on-time resources are critical for expediting a profitable business. Frequent disruption and lack of resources affect the trust and level of collaboration among the SC partners, which also leads to an increase in the complexity level within the entire value chain (Suh, 2005).

- *Organizational structure*: To be more productive, it is essential to efficiently structure an organization. An inappropriate organizational structure leads to wasted time and creates confusion in the chain of command and complexity to the entire value chain (Wilding, 1998; Serdarasan, 2013). An organizational structure needs to be clear, flexible, and highly stable, as rigid and frequent changes in the structure create complexity.

- *Logistics and transportation*: Freight transportation is considered the largest logistics expense for a number of companies (Triki et al., 2017; Triki et al., 2020). The performance of the SC is highly dependent on the mode of transportation and available logistics infrastructure. Inadequate and inefficient management of logistics and transportation often creates complexity that affects the productivity of the entire SC (Hesse and Rodrigue, 2004; Stadtler, 2015; Sivadasan et al., 2010). A flexible, multimodal, and robust logistics and transportation network is necessary for a dynamic SC.

- *Marketing*: The profitability of a company is significantly affected by proper marketing and sales strategies. In addition to productivity, effective and efficient management of marketing and sales strategies improves overall SC performance (Wilding, 1998; Wong et al., 2015). Improper management of this driver generates complexity within the SC network.

- *Product development*: In the product development cycle, the selection of architecture influences its manufacturability and assemble ability (Loch et al., 2003; Nepal et al., 2012). Overall, SCC heavily depends on product architecture and whether it is modular or integral. Therefore, having an efficient R&D facility with an effective product development unit leads to a less complex SC.

- *Customer need*: To remain competitive, it is critical to understanding up-to-date customers' needs (Piya et al., 2016). To meet a variety of customer needs, increasing the level of product and service options is necessary. However, when customers have frequently changing needs in terms of additional product features create complexity in the SC (Krishnan and Gupta, 2001; Da Silveira, 2005).

- *Competitor action*: Given the increasing level of competition in today's business environment, companies need to continuously monitor the action of their competitors.

Accordingly, they need to trigger reactions to keep pace and be competitive in the market. Any action from the competitor will affect the company's product design, production, marketing, and SC integration (Hashemi et al., 2013). Therefore, having more competitors with constant action creates more complexity in the SC.

- *Technological innovation*: To keep pace with technological advancements, companies should welcome any technological innovation. However, such innovation requires a company to establish new production lines, materials, processes, and even new SC partners, which increase SCC (Blecker et al., 2005; Hashemi et al., 2013; Gunasekaran et al., 2014). In addition, frequent incremental or disruptive innovation in technology from competitors or developed by the organization and its SC partner creates complexity in terms of adapting to the new technology or improvement on the existing technology.

- *Government regulations, laws, and legal issues*: To manage a company's SC network smoothly, it is necessary to follow the rules and regulations imposed by the government. Having fewer legal hurdles and regulations to follow in different jurisdictions is better for the entire SC (Mohrschladt, 2007). Frequent changes in government regulations and imposition of new restrictions specific to the given product/service lead to more complexity in managing the SC (Serdarasan, 2013).

- *Organizational standards*: Acquiring and maintaining organizational standards is key to ensuring high-quality products or processes. It is therefore critical to meet organizational standards (e.g., ISO and ASME) to remain competitive. However, maintaining standards is not an easy task, and doing so may often create additional challenges for the entire SC since it may be insufficient to only acquire the standards by parent organization (Ellram, 1991; Li et al., 2006). Therefore, from the complexity perspective, for the product or company to remain competitive, embracing less organizational standards is preferred.

- *Process synchronization*: In any SC network, maintaining synchronization between collaborative processes is crucial. Inadequate process synchronization results in complexity between SC partners and creates unexpected chaos and confusion (Wilding, 1998).

- *Forecasting error*: Inefficient forecasting and lack of proper and real-time information flow between SC partners create a bullwhip effect and delivery delay. They also lead to wider fluctuations in the order delivery process, which might result in operational complexity in the entire value chain (Chen et al., 2000; Govindan et al., 2010). Therefore, a high forecasting error in the SC network will disrupt the smooth functioning of the entire chain.

- *Information technology*: The use of insufficient and incompatible information technologies by SC partners results in distorted information sharing that negatively affects the value chain (Serdarasan, 2013). The more compatible the information technology used by the entire SC network, the better the flow of information and communication, thereby reducing complexity.

- *Number of suppliers*: It is not desirable to have too many or too few suppliers. To manage efficiently and to be successful, a company should select an accurate as possible number of suppliers within the SC network. An increase in the number of suppliers will increase the level of complexity in terms of SC coordination and follow-up (Wu and Choi, 2005; Goffin et al., 2006).

- *Supplier location*: In terms of coordination and follow-up, physical interaction is better than virtual interaction. Distance between the parent company and suppliers' locations often creates complexity that is caused by difficulty in adequately monitoring and controlling suppliers to achieve productivity (Sivadasan et al., 2010). Therefore, suppliers should be located as near the original equipment manufacturer as possible.

- *Number and variety of customers*: In business, increasing the number of potential customers to maximize revenue is expected. However, increasing the number of customers and the heterogeneity of their needs often creates added complexity because of the need to increase levels of customer relationship management, demand management, and order management (Bozarth et al., 2009; Kavilal et al., 2017).

- *Company culture*: Culture affects productivity in industrial establishments (Pathak et al., 2007). Cultural differences between SC partners might negatively affect the level of productivity, innovation, and the issue of transparency. Therefore, having SC partners with a similar working culture is preferred, as it reduces complexity and improves SC performance.

- *SC network*: For a successful business, choosing SC partners with the right competencies is essential. Any mismatch among SC partners results in an incompatible SC network design and inefficient SC operations, which leads to complexity (Shah, 2005; Serdarasan, 2013).

3. SCC Dimensions

Past researchers categorized complexity drivers into various dimensions. Vachon and Klassen (2002) used two main dimensions of technology and information processing to classify the drivers. These dimensions were further sub-classified into uncertainty, complicatedness, management systems, and product/process. On the other hand, Perona and Miragliotta (2004) classified complexity drivers into the dimensions of inbound and outbound logistics, product development, production process, production engineering, and sales process. Cagliano et al. (2009) used the dimensions of utilization, productivity, and effectiveness to measure the complexity of the SC. de Leeuw et al. (2013) classified the SCC drivers into five dimensions of numerousness, variability, diversity, visibility, and uncertainty. From the literature review, it is evident that there is no specific method to classify SCC drivers into dimensions. In this research, the SCC drivers discussed in Section 2 were classified into various dimensions based on experts' opinions. The classification of drivers helps assign different weights to different dimensions while measuring the SCC level and depends on the degree of influence the dimension has on SCC.

Five experts took part in the brainstorming session. The number of experts was based on the finding that most studies in the existing literature have consulted between 5 and 15 experts each (Qureshi et al., 2007). The experts who participated have worked in an organization operating in the Middle East for more than four decades. The organization is one of the reputed corporate houses in the Middle East and has diversified business interests in areas such as agriculture, pharmaceuticals, and fast-moving consumer goods (FMCG). These experts considered the domain of the SCC drivers for their classification into the SCC dimensions. For example, as shown in Table 1, complexity drivers m11, m12, m13, m14, and m15 are classified under the dimension "strategic management" because all these drivers are related to the strategic issue and the management of these drivers should be considered at the highest level in the management hierarchy (Piya et al., 2017). Altogether, the drivers were classified into five dimensions as shown in Table 1.

Table 1: Complexity driver and its dimensions

Complexity Dimension (k)	*Complexity Driver (m)*				
Strategic management (k1)	Organizational structure (m11)	Product development (m12)	Technological innovation (m13)	Organizational standard (m14)	Government regulation (m15)
Production planning and control (k2)	Product variety (m21)	Manufacturing process (m22)	Planning and scheduling (m23)	Resource constraint (m24)	Logistics and transportation (m25)
Supplier base (k3)	Process synchronization (m31)	Number of suppliers (m32)	Supplier location (m33)	Company culture (m34)	SC network (m35)

Marketing and sales (k4)	Marketing (m41)	Customer need (m42)	Competitor action (m43)	Number and variety of customer (m44)	-
Information and Communication (k5)	Internal communication and information sharing (m51)	Forecasting error (m52)	Information technology (m53)	-	-

4. Proposed Method

This study adopted a multicriteria decision approach in developing a mathematical model, which is a combination of the analytical hierarchy process (AHP) and grey relational analysis (GRA). The combination of such methods is preferred over other techniques because of the ability to convert the inheritance and interdependence of SCC drivers into a single numeric value (Arunachalam et al., 2019). After identifying complexity drivers and then clustering them into various complexity dimensions in Section 3, the weight of each dimension was calculated based on the AHP method before applying the GRA method. This was due to the fact that the GRA method provides equal weight to the entire dimension that affects the level of SCC. However, in reality, the weight of each dimension can be assigned according to the influence of each dimension on SCC. After determining the weight, the GRA method was implemented to calculate the grey relational grade (GRG). The results of the AHP and GRA methods were then integrated to determine the complexity level of the SC. The details of the AHP and GRA methods are discussed hereafter.

4.1 AHP Method

AHP is a popular and widely used multicriteria decision support method that was introduced by Saaty in 1986 (Saaty 1990). The method helps decision makers structure a complex problem into a simple hierarchy based on quantitative data as well as judgments, feelings, and other factors that influence the decision (Bayazit, 2005; Sharma and Dubey, 2010). It involves experts assigning weights to several criteria using the concept of natural pairwise comparison. Such a comparison represents the ratio of weight among criteria and expresses the relative importance of one criterion over others for a common objective.

The AHP method has been used extensively in different domains such as e-business improvement (Lee and Kozar, 2006), quality and performance measurement (Kannan, 2010; Min, 2010), railway scheduling (Isaai et al., 2011), inventory and disaster management (Borade et al., 2013; Nivolianitou et al., 2015), workshop evaluation (Lucas et al., 2017), systems design (Ulloa et al., 2018), and many more. It has also been extensively applied for SC-related issues such as SC risk assessment (Dong and Cooper, 2016), supplier selection (Chai et al., 2013; Dweiri et al., 2016), sustainable SC adoption (Luthra et al., 2016), SC performance evaluation (Yang, 2009), and optimization of SC networks (Sharma, Moon, and Bae, 2008). Some hybrid applications of AHP with ANP, TOPSIS, DEA, and GRA can also be widely observed in the literature (Bruno et al., 2012). The AHP method starts with the construction of a problem into the hierarchical structure. Figure 1 shows the hierarchical structure of the problem that this study is addressing. The following steps are followed thereafter.

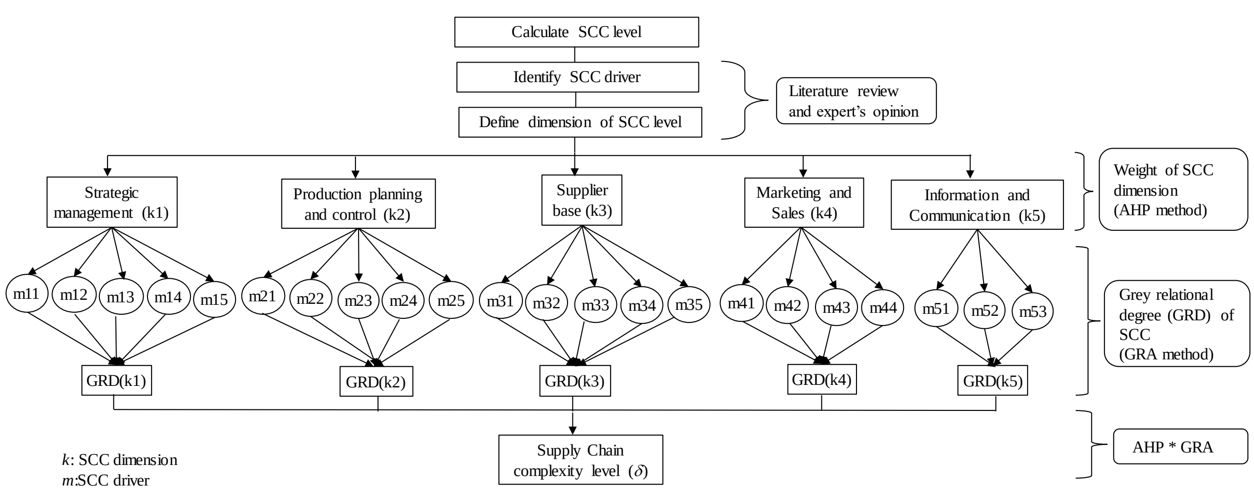

Figure 1: Conceptual framework to calculate SC complexity level

4.1.1 Perform pairwise comparison

Once the criteria are determined and the problem is structured, they are evaluated. Each pair is compared, and the importance of one criterion over the others is discerned by the objectives. In our problem, the criteria refer to SCC dimensions. Expert opinion is solicited for the comparison. The comparison results in a scoring matrix (V_l) obtained from the l^{th} expert (l = 1, 2,…., L), the size of which is equal to n x n, where n represents the number of SCC dimensions that are compared. Each element (a_{ijl}) of matrix V_l represents a numeric value obtained from the comparison according to the Saaty scale, which varies from 1 to 9, or their reciprocals, as shown in Table 2. If $i = j$, then a_{ijl} will be equal to 1. In Equation (1), l in the matrix shows that the element a_{ijl} is the opinion of the l^{th} expert.

$$V_l = \begin{bmatrix} a_{11l} & a_{12l} & \dots & a_{1nl} \\ a_{21l} & a_{22l} & \dots & a_{2nl} \\ \dots & \dots & \dots & \dots \\ a_{n1l} & a_{n2l} & \dots & a_{nnl} \end{bmatrix} \text{ where, } a_{ijl} = 1/a_{jil} \text{ and } i=1,\dots,n;\ j=1,\dots,n;\ l=1,\dots,L \quad (1)$$

4.1.2 Calculate the geometric mean of expert opinion

Once all the experts individually provided their relative importance scores, the next step was to calculate the aggregate score of the experts. The most common technique to arriving at an aggregate score is using the geometric mean (Grošelj et al., 2015), which is shown in Equation (2). Equation (3) shows the aggregate score matrix.

$$b_{ij} = \sqrt[L]{\prod_{l=1}^{L} a_{ijl}} \qquad \forall i,j \text{ and } i,j \in k \quad (2)$$

$$V = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix} \quad (3)$$

Table 2: Importance scale of criteria for pairwise comparison

Value	Definition
1	*i* and *j* are equally important
3	*i* is slightly more important than *j*
5	*i* is important than *j*
7	*i* is much important than *j*
9	*i* is absolutely important than *j*
2, 4, 6, 8	Intermediate values

4.1.3 Normalize the aggregate score matrix

Priority weights derived from the judgments, including the consistency of judgments, were computed using the principal right eigenvector method, as shown in Equation (4).

$$VW=\lambda_{\max} W \quad (4)$$

In the above equation, W refers to the normalized eigenvector, and λ_{max} is the principal eigenvalue of the pairwise comparison matrix V of order n. Such an eigenvector is computed by raising the matrix V to a large power until the normalized row sum of the resulting matrix converges to a limiting value. The normalized value is calculated, as shown in Equation (5). Equation (6) represents the normalized matrix.

$$p_{ij} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{n} b_{ij}^2}} \qquad \forall i, j \text{ and } i, j \in k \quad (5)$$

$$W = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \quad (6)$$

4.1.4 Calculate the weight of the SCC dimension

Finally, the weight of the SCC dimension can be calculated using Equation (7). Here, weight represents the influence of one complexity dimension as compared to others in terms of the SCC level.

$$w_i = \frac{\sum_{j=1}^{n} p_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}} \quad \forall i \in k \quad i = 1, 2, \dots, k \quad (7)$$

4.1.5 Check consistency

Saaty (1990) defined consistency matrix as a matrix whose consistency ratio (*CR*) is lower than 10 percent. If the *CR* is greater than 0.1, then the decision maker should revise his/her decision on the pairwise comparison in Section 4.1.1.

$$CR = \frac{CI}{RI}, \text{ where} \quad (8)$$

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (9)$$

The random inconsistency index (*RI*) in Equation (8) represents the average consistency index for criteria *n* over a number of entries of same-order reciprocal matrices. For $n = 5$, $RI = 1.12$ (Kannan, 2010). Therefore, the *CR* is a measure of how a given matrix compares with a purely random matrix in terms of their consistency indices. λ_{max} in the equation can be calculated using Equation (10).

$$\lambda_{max} = \frac{\sum_{j=1}^{n} b_{ij} w_j}{w_i} \quad (10)$$

4.2 Grey Relational Analysis

Deng Ju-Long proposed the grey relational theory based on the grey set by combining concepts of system theory, space theory, and control theory (Ju-Long, 1982). Grey relational analysis calculates and unifies grey relational coefficients for all quality characteristics whether they are of the "larger the better" or "smaller the better" situations (Nelabhotla et al., 2016). It means that GRA helps to convert multiple performance indicators into a single GRG. One of the significant advantages of the grey relational theory is that it can generate satisfactory outcomes using a relatively small amount of data (Yang and Chen, 2006). It has been widely used for the optimization of multiple process parameters in various fields such as health care (Xuerui and Yuguang, 2004; Alam et al., 2019), product development (Chan, 2008), reliability analysis (Zhou et al., 2016), pattern recognition (Sun et al., 2018), materials and manufacturing (Nelabhotla et al., 2016; Shinde and Pawar, 2017), and many more. However, only a few papers have used the GRA method (stand-alone or in combination with other methods) for issues related to the SC (Yang and Chen, 2006; Hashemi et al., 2015; Rajesh and Ravi, 2015; Pang et al., 2017; and Badri et al., 2017). This research applied the GRA method because to minimize SCC, drivers such as "product development" and "process synchronization" need to be maximized (i.e., "more is better" situation). On the other hand, for drivers such as "forecasting error" and "competitor action," less is better. The GRA method helps to integrate multiple factors/parameters with the opposite objective function into a single GRG. The following steps are implemented to obtain a GRG using the GRA method.

4.2.1 Obtain the linguistic scale on SCC drivers

The linguistic scale on the driver (m = 1, 2,….., M) associated with the complexity dimensions (k = 1, 2,…., K) is rated by the experts (l = 1, 2,…., L). To avoid ambiguity in dealing with imprecise data, the linguistic scale as shown in Table 3 is used. Each linguistic variable has lower ($\underline{y}_{klm}$)

and upper ($\overline{y}_{klm}$) values. The decision matrix (D_k) to calculate the GRG for dimension k is shown in Equation (11). Equation (12) shows that in Equation (11), y_{klm} has two values depending on the lower and upper values of linguistic variables.

Table 3: Linguistic variable and associated value

Definition	Notation	Value
Very — poor, low, near, less effective	VP	0–2
Poor, low, near, less effective	P	2–4
Medium, fair	M	4–6
Good, high, far, effective	G	6–8
Very — good, high, far, effective	VG	8–10

$$D_k = \begin{bmatrix} y_{k11} & y_{k12} & \cdots & y_{k1M} \\ y_{k21} & y_{k22} & \cdots & y_{k2M} \\ \cdots & \cdots & \cdots & \cdots \\ y_{kL1} & y_{kL2} & \cdots & y_{kLM} \end{bmatrix} \tag{11}$$

$$y_{klm} = \left(\underline{y}_{klm}, \bar{y}_{klm}\right) \tag{12}$$

4.2.2 Normalize the value

The expert's value obtained in Section 4.2.1 is normalized using formulas in Equations (13) and (14). The use of the formula depends on whether the driver represents a "more is better" or a "less is better" scenario. Equation (18) shows the normalized grey decision matrix. Equations (15) and (19) show that x_{klm} and D_k^* will have two values depending on the lower and upper values of y_{klm} and x_{klm} respectively.

$$x_{klm} = \frac{[y_{klm} - min(y_{km})]}{max(y_{km}) - min(y_{km})} \quad (13)$$

$$x_{klm} = \frac{[max(y_{km}) - y_{klm}]}{max(y_{km}) - min(y_{km})} \quad (14)$$

In Equations (13) and (14),

$$x_{klm} = \left(\underline{x}_{klm}, \bar{x}_{klm}\right) \quad (15)$$

$$\max(y_{km}) = \underset{1 \le l \le L}{max}(y_{klm}) \text{ where, } y_{klm} \in (\underline{y}_{klm}, \bar{y}_{klm}) \quad (16)$$

$$\min(y_{km}) = \underset{1 \le l \le L}{min}(y_{klm}) \text{ where, } y_{klm} \in (\underline{y}_{klm}, \bar{y}_{klm}) \quad (17)$$

$$D_k^* = \begin{bmatrix} x_{k11} & x_{k12} & \cdots & x_{k1M} \\ x_{k21} & x_{k22} & \cdots & x_{k2M} \\ \cdots & \cdots & \cdots & \cdots \\ x_{kL1} & x_{kL2} & \cdots & x_{kLM} \end{bmatrix} \quad (18)$$

In Equation (18), $D_k^* = \left(\underline{D}_k^*, \overline{D}_k^*\right)$ (19)

4.2.3 Establish the reference alternative

The reference alternative reflects the best normalized value on all SCC drivers related to the corresponding complexity dimension.

$$x_{km}^0 = \underset{1 \le l \le L}{max}(x_{klm}) \quad (20)$$

4.2.4 Measure the difference between the reference alternative and the normalized value

The difference between the reference alternative and the normalized value represents the distance of the expert’s normalized value from the best value.

$$\vartheta_{klm} = x_{km}^0 - x_{klm} \quad (21)$$

In Equation (21), $\vartheta_{klm} = \left(\underline{\vartheta}_{klm}, \bar{\vartheta}_{klm}\right)$ (22)

The difference matrix is shown in Equation (23).

$$\Delta_k = \begin{bmatrix} \vartheta_{k11} & \vartheta_{k12} & \cdots & \vartheta_{k1M} \\ \vartheta_{k21} & \vartheta_{k22} & \cdots & \vartheta_{k2M} \\ \cdots & \cdots & \cdots & \cdots \\ \vartheta_{kL1} & \vartheta_{kL2} & \cdots & \vartheta_{kLM} \end{bmatrix} \tag{23}$$

In Equation (23), $\Delta_k = \left(\underline{\Delta}_k, \bar{\Delta}_k\right)$ (24)

As shown in Equations (22) and (24), ϑ_{klm} and Δ_k will have lower and upper values depending on the lower and upper values of x_{klm} and ϑ_{klm}, respectively.

4.2.5 Calculate the SCC grey relational coefficient

The grey relational coefficient (GRC) helps to express the correlation between normalized data and the ideal result for each complexity driver.

$$G_{klm} = \frac{\min_l \min_m (\underline{\vartheta}_{klm}) + \alpha\left\{\max_l \max_m (\bar{\vartheta}_{klm})\right\}}{\vartheta_{klm} + \alpha\left\{\max_l \max_m (\bar{\vartheta}_{klm})\right\}} \tag{25}$$

In Equation (25), $G_{klm} = \left(\underline{G}_{klm}, \bar{G}_{klm}\right)$ depending on ϑ_{klm}. (26)

α in Equation (25) is a distinguishing coefficient, the value of which varies within (0, 1).

4.2.6 Calculate the SCC grey relational degree

The grey relational degree (GRD) is the GRC of complexity dimension *k*. It is calculated by taking the average GRC of all the drivers associated with SCC dimension *k*.

$$G_{kl} = \frac{1}{M}\sum_{m=1}^{M} G_{klm} \tag{27}$$

In Equation (27), $G_{kl} = \left(\underline{G}_{kl}, \bar{G}_{kl}\right)$ depending on the value of $G_{klm.}$ (28)

4.2.7 Calculate the SCC grey relational grade

The GRG is a weighted average value of the GRD of the entire SCC dimensions. The weight obtained from the AHP method is used to calculate the GRG.

$$G_l = \sum_{k=1}^{K} G_{kl} * w_k \tag{29}$$

In Equation (29), $G_l = \left(\underline{G}_l, \bar{G}_l\right)$ depending on G_{kl} (30)

4.2.8 Calculate the grey SCC level

The grey SCC level (δ) represents the average of the unified GRG obtained from multiple experts.

$$\delta = 1 - \sqrt[L]{\prod_{l=1}^{L} \left(\frac{1}{2}\right) \left(\underline{G_l} + \overline{G}_l\right)} \tag{31}$$

The value of δ varies from (0, 1), where 0 represents the idle situation, i.e., the SC without any complexity, and 1 represents a highly complex SC.

5. Case Study

To demonstrate the applicability of the proposed method, a case study was conducted in a company that produces FMCG. The industry belongs to the same corporate house whose five experts helped to classify complexity drivers into SCC dimensions (discussed in Section 3). To apply the proposed method, at first, the same experts were contacted to calculate the weight of the SCC dimensions. They were requested to give weight to the dimensions based on pairwise comparison according to the linguistic variable in Table 2. The weighted matrices received from the five experts were then unified based on Equation 2. Table 4 shows the unified weighted matrix.

Table 4: Experts' unified pairwise comparison matrix for AHP method

Dimension (k)	1	2	3	4	5
Strategic management (1)	-	4.47	2.83	4.47	1.73
Production planning and control (2)	0.22	-	0.41	2	0.41
Supplier base (3)	0.35	2.45	-	3.46	0.71
Marketing and sales (4)	0.22	0.5	0.29	-	0.29
Information and Communication (5)	0.58	2.45	1.41	3.46	-

The unified pairwise comparison matrix was further analyzed using Equations (5) and (7) to obtain the weight for each dimension, as shown in Table 5.

Table 5: Weight of SCC dimension based on AHP result

Dimension (k)	Weight (w_k)	Rank
Strategic management (1)	0.40	1
Production planning and control (2)	0.10	4
Supplier base (3)	0.19	3
Marketing and sales(4)	0.07	5
Information and Communication (5)	0.24	2

In Table 4, the consistency of the pairwise comparison is also analyzed. The results show that the λ_{max} is 5.12 (Equation [10]), RI when K is 5 is 1.15, and CI is 0.0292 (Equation [9]). From Equation (8), the CR is equal to 0.02614, which is considerably less than the acceptable value of 0.1. Therefore, the pairwise comparison of experts on dimensions is consistent.

The case study then focused on measuring the SCC level of the company that produces FMCG goods. The company has a broad market that spans the GCC as well as some North African countries. The company has multiple supply chain partners, especially for raw material and semi-finished products, spanning local as well as overseas suppliers. To apply the GRA method, a questionnaire was prepared based on the drivers for each SCC dimension (Appendix A) and submitted to the five experts working in a managerial position in the production, marketing, supply chain, and administrative departments. All these experts have working experience of more than ten years. Table 6 shows the linguistic variables received from the experts for SCC drivers and their associated values.

Table 6: Linguistic variables received from the experts and associated values

SCC dimension (*k*)	SCC Driver (m)	Expert's linguistic variable					Associated value of linguistic variable									
		1	2	3	4	5	Exp 1		Exp 2		Exp 3		Exp 4		Exp 5	
							L	H	L	H	L	H	L	H	L	H
	m11	VG	G	G	VG	G	8	10	6	8	6	8	8	10	6	8
	m12	G	M	VG	P	G	6	8	4	6	8	10	2	4	6	8
	m13	P	P	M	VP	M	2	4	2	4	4	6	0	2	4	6
	m14	G	G	G	VG	G	6	8	6	8	6	8	8	10	6	8
1	m15	M	P	M	G	VP	4	6	2	4	4	6	6	8	0	2
	m21	P	VP	P	P	M	2	4	0	2	2	4	2	4	4	6
	m22	M	M	P	P	P	4	6	4	6	2	4	2	4	2	4
	m23	G	M	M	G	M	6	8	4	6	4	6	6	8	4	6
	m24	G	G	P	P	M	6	8	6	8	2	4	2	4	4	6
2	m25	VP	P	P	VP	M	0	2	2	4	2	4	0	2	4	6
	m31	G	VG	M	G	VG	6	8	8	10	4	6	6	8	8	10
	m32	M	M	P	G	P	4	6	4	6	2	4	6	8	2	4
	m33	G	G	M	M	M	6	8	6	8	4	6	4	6	4	6
	m34	M	P	P	M	P	4	6	2	4	2	4	4	6	2	4
3	m35	G	G	M	G	G	6	8	6	8	4	6	6	8	6	8
	m41	M	M	M	P	P	4	6	4	6	4	6	2	4	2	4
	m42	P	VP	VP	P	VP	2	4	0	2	0	2	2	4	0	2
	m43	M	P	G	P	M	4	6	2	4	6	8	2	4	4	6
4	m44	G	G	M	VG	VG	6	8	6	8	4	6	8	10	8	10
	m51	VP	P	P	M	M	0	2	2	4	2	4	4	6	4	6
	m52	M	P	P	M	P	4	6	2	4	2	4	4	6	2	4
5	m53	G	M	G	G	VG	6	8	4	6	6	8	6	8	8	10

According to the GRA steps, the linguistic variables are normalized depending on a "more is better" or "less is better" situation. Drivers m11, m12, m22, m25, m31, m34, m41, m51, m53, and m54 represent a "more is better" scenario from the SCC perspective. These drivers are normalized using Equation (13). On the other hand, Equation (14) is used to normalize the remaining drivers. The normalized matrix for the dimension "strategic management" is shown below.

$$\left(\underline{D}_1^*, \overline{D}_1^*\right) = \begin{bmatrix} 0.8, 1.0 & 0.6,0.8 & 0.6,0.8 & 0.2,0.4 & 0.4,0.6 \\ 0.6,0.8 & 0.4,0.6 & 0.6,0.8 & 0.2,0.4 & 0.6,0.8 \\ 0.6,0.8 & 0.6,0.8 & 0.4,0.6 & 0.2,0.4 & 0.4,0.6 \\ 0.8,1.0 & 0.2,0.4 & 0.8,1.0 & 0.0,0.2 & 0.2,0.4 \\ 0.6,0.8 & 0.6,0.8 & 0.4,0.6 & 0.2,0.4 & 0.8,1.0 \end{bmatrix}$$

Based on the normalized matrix for the given dimension, the reference alternative is selected for the drivers. For "strategic management," 1.0, 0.8, 1.0, 0.4, and 1.0 represent the reference alternative of m11, m12, m13, m14, and m15, respectively. The difference between the alternative and the reference alternative is measured using Equation (21). The measured distance is then used in Equation (25) to compute the SCC GRC. In Equation (25), α is assumed to be 0.5, as some parameters need to be minimized and others maximized. It gives equal preference to the maximum as well as the minimum absolute deviations. For "strategic management," $\min_{l} \min_{m} (\underline{\vartheta}_{klm})$ and $\max_{l} \max_{m} (\overline{\vartheta}_{klm})$ in the equation will be equal to 0 and 1, respectively, as the maximum and minimum normalized values in the above matrix are 1 and 0, respectively. The GRC matrix for the dimension "strategic management" is shown below.

$$\left(\underline{G}_{1lm}, \overline{G}_{1lm}\right) = \begin{bmatrix} 0.71, 1.0 & 0.56,0.71 & 0.56,0.71 & 0.38,0.45 & 0.45,0.56 \\ 0.56,0.71 & 0.45,0.56 & 0.56,0.71 & 0.38,0.45 & 0.56,0.71 \\ 0.56,0.71 & 0.71,1.0 & 0.45,0.56 & 0.38,0.45 & 0.45,0.56 \\ 0.71,1.0 & 0.38,0.45 & 0.71,1.0 & 0.33,0.38 & 0.38,0.45 \\ 0.56,0.71 & 0.56,0.71 & 0.45,0.56 & 0.38,0.45 & 0.71,1.0 \end{bmatrix}$$

The data in the second and third columns of Table 7 (k = 1), which are calculated based on the corresponding GRC matrix and using Equation (27), represent the SCC GRD for the dimension "strategic management". The table also shows the GRD of all other dimensions. The GRD was then integrated with the weight obtained from the AHP method (Table 5) to obtain the GRG. Integration was performed based on Equation (29).

Table 7: SCC grey relational degree (GRD) and SCC grey relational grade (GRG)

Expert	GRD for five dimensions										GRG	
	k=1		k=2		k=3		k=4		k=5			
	$\underline{G}_{1l}$	$\overline{G}_{1l}$	$\underline{G}_{2l}$	$\overline{G}_{2l}$	$\underline{G}_{3l}$	$\overline{G}_{3l}$	$\underline{G}_{4l}$	$\overline{G}_{4l}$	$\underline{G}_{5l}$	$\overline{G}_{5l}$	$\underline{G}_{l}$	$\overline{G}_{l}$
1	0.53	0.69	0.42	0.51	0.46	0.57	0.46	0.57	0.43	0.53	0.48	0.60
2	0.50	0.63	0.48	0.60	0.48	0.62	0.53	0.68	0.43	0.53	0.48	0.60
3	0.51	0.66	0.47	0.58	0.46	0.57	0.50	0.64	0.49	0.61	0.49	0.62
4	0.51	0.66	0.44	0.54	0.46	0.57	0.46	0.57	0.51	0.63	0.49	0.62
5	0.53	0.69	0.44	0.54	0.53	0.68	0.47	0.60	0.53	0.68	0.52	0.66

Finally, the GRGs of all experts were unified by Equation (31) to obtain the grey SCC level.

$$\delta = 1 - \sqrt[5]{\frac{1}{32}[(0.48 + 0.6) * (0.48 + 0.6) * (0.49 + 0.62) * (0.49 + 0.62) * (0.52 + 0.66)]}$$

$=0.44$

5.1 Result Interpretation

The following are interpretations of the derived results.

- δ varies from (0, 1), where 0 means that the system is not complex at all and 1 means that the system is highly complex. Therefore, having δ equal to 0.44 for the company in the case study shows that there is still ample room for improvement to minimize complexity in the company's SC.
- Having δ equal to 0 may not be practically possible. However, companies should always aim to minimize the value of δ. δ can be improved by reducing the complexity related to the driver where more opportunities for improvement are available. For the company in the case study, the grey relational degrees of m14, m22, m25, m33, m34, m44, and m51 are weak (Table 8). Calculating the grey SCC level based only on these drivers shows that δ_p is equal to 0.59. It means that the SCC level of δ equal to 0.44 for the company is because δ_p is very high.

Therefore, an improvement of these drivers will help minimize the overall SCC level of the company.

Table 8: Drivers with poor GRD and corresponding GRG

Expert	Drivers with poor GRD										GRG	
	m14		Average (m22, m25)		Average (m33, m34)		m44		m51			
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
1	0.38	0.45	0.39	0.47	0.42	0.51	0.38	0.45	0.36	0.42	0.39	0.46
2	0.38	0.45	0.42	0.51	0.38	0.45	0.38	0.45	0.36	0.42	0.38	0.45
3	0.38	0.45	0.38	0.45	0.42	0.51	0.45	0.56	0.42	0.51	0.40	0.48
4	0.33	0.38	0.36	0.42	0.45	0.56	0.33	0.38	0.51	0.63	0.40	0.48
5	0.38	0.45	0.42	0.51	0.42	0.51	0.33	0.38	0.42	0.51	0.41	0.49

$$\delta_p = 1 - \sqrt[5]{\frac{1}{32}[(0.39 + 0.46) * (0.38 + 0.45) * (0.40 + 0.48) * (0.40 + 0.48) * (0.41 + 0.49)]}$$

=0.59

- For the company in the case study, as suggested by the AHP method, "strategic management" and "information and communication" are the most important dimensions to minimize SCC. Therefore, companies should focus more on m14 and m51 to minimize complexity in their SC rather than m22, m25, and m44 since the weights of the dimensions corresponding to m22, m25, and m44 are comparatively less.

5.2 Sensitivity Analysis

The GRG is significantly affected by the weight of the complexity dimension, which is based on the expert's subjective judgment. A change in the weight of the dimension will affect the GRG as well as the drivers that need more attention to minimize the SCC level. The effect of weight on the GRG is analyzed by considering five different cases, with each case having five different scenarios. In Case 1, a higher weight is assigned to the complexity dimension "strategic management." In this case, the weight for strategic management is assigned from (0.3-0.7) in the count of 0.1 to generate five different scenarios. The remaining weight (total weight of all dimensions is 1) is then distributed equally to other dimensions. Similarly, the other four cases are also developed. Case 2, Case 3, Case 4, and Case 5 represent the cases where higher weights are assigned to "information and communications," "supplier base," "production planning and control," and "marketing and sales," respectively.

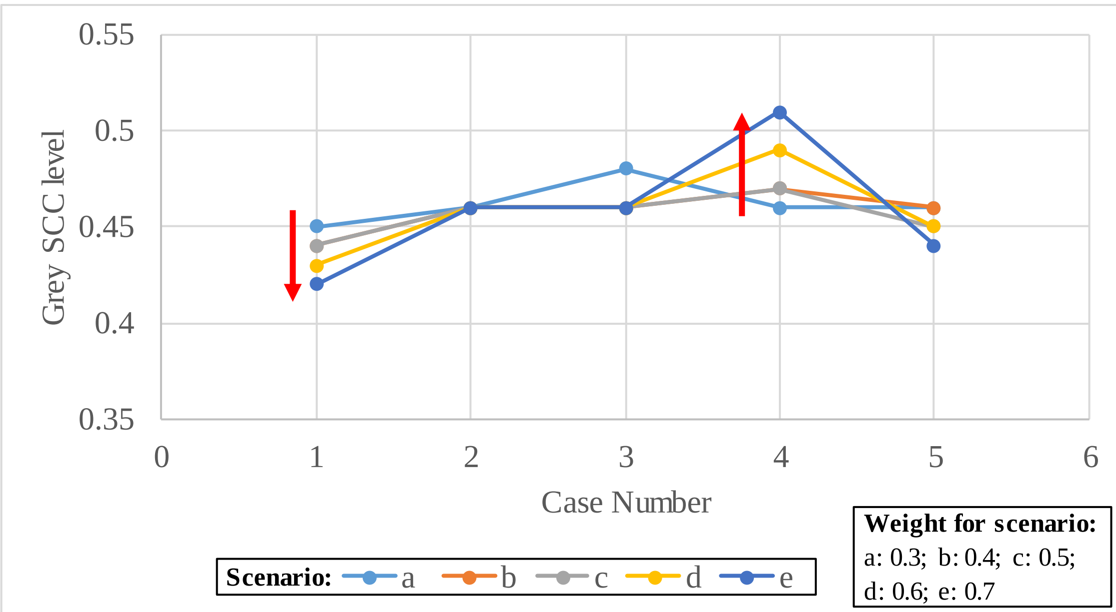

Figure 2: Effect of weight on Grey SCC level

Figure 2 shows the effect of weight on the grey SCC level for the company in the case study. From the figure, it is evident that Case 1 and Case 4 have a significant impact on weight. In Case 1, with the increased emphasis on strategic management, the level of complexity in the SC decreases as indicated by a reduction in GRG SCC level when the weight increases from (0.3-0.7). However, the opposite trend is observed in Case 4. As the weight on production planning and control increases, the GRG SCC level also increases. No effect is observed in Case 2. Minor effects are observed in Case 3 and Case 5. In both cases, the GRG SCC level is inversely proportional to weight. The analysis shows that strategic management has the highest effect on weight to improve the SCC level of the company.

6. Implications and Limitations

Even though complexity is a part of any SC, companies should seek ways to minimize it in order to improve the performance of their overall SC. Complexity related to the flows of materials, funds, and information between the SC not only reduces SC efficiency but is also seen as a key antecedent to disruptions in the SC (Wang et al., 2018). Supply chain complexity may arise because of various reasons and at any level (upstream, midstream, or downstream). To minimize complexity, it is imperative that companies identify and understand the drivers and their levels that are responsible for the complexity. The identification of drivers helps organizational managers take necessary precautions, invest required efforts, and channel available resources to overcome the complexity associated with their SC network. Moreover, due to the classification of the complexity drivers into dimensions, it would be quite helpful for the managers to focus on the ones that are most critical and are responsible for the complexity in the SC.

It is worth mentioning that this study has some limitations regarding the management of SCC. The study has presented twenty-two generic drivers of SCC and classified them into five dimensions. Based on these drivers and dimensions, a mathematical model was presented to calculate the level of complexity in the SC. It is possible that there may be another driver of SCC related to the specific business domain. Moreover, in the future, new research may identify new driver(s), and the driver(s) may fall under any defined complexity dimension. In such a situation, there will be a need to reformulate the model to incorporate additional drivers and recalculate the complexity level. However, the proposed model can easily accommodate new driver(s) and dimensions with minor modifications and calculate the complexity level. Besides, the study was tested in only one case company, so this may not validate the presented approach and generalize the study outcomes for a wider community.

7. Conclusions and Future Research Direction

This study discussed various drivers of SCC based on the literature review and measured the level of complexity created by these drivers within the SC. As some drivers needed to be minimized and others maximized to minimize SCC, the integrated AHP and GRA methods were used to measure the level of complexity. The case study of a multinational company demonstrates the applicability and practical implications of the proposed method. The case study concluded that in order for the company to minimize complexity in its SC, it needs to focus its attention on drivers such as government regulation, internal communication and information sharing, and company culture. With minor modifications, the proposed method can be used to compare the complexity level of various SCs.

The effectiveness of the SC is defined based on various performance measures (Gunasekaran and Kobu, 2007). The complexity dimensions and drivers discussed in this paper may or may not affect all SC performance measures, or they may have varying degrees of effects on the performance measures. This research can be extended to determine the effects of complexity drivers and their magnitude on various performance measures of the SC such as cost, supplier responsiveness, and innovation. Further, incorporating a solution method to improve one driver of complexity may trigger another driver, or it may increase the level of complexity created by other drivers. Therefore, another interesting avenue of research may be to understand the knock-on effect of one driver over others so that companies can focus on improving the drivers that will have less or no knock-on effects on other drivers.

References

Aitken, J., Bozarth, C. and Garn, W. (2016), "To eliminate or absorb supply chain complexity: a conceptual model and case study," *Supply Chain Management*, 21 (6), 2413–2427.

Alam, K., Al-Ghaithi, A., Piya, S. and Saleem, A. (2019), "In-vitro experimental study of histopathology of bone in vibrational drilling" *Medical engineering & physics*, 67, 78-87.

Allesina, S., Azzi, A., Battini, D. and Regattieri, A. (2010), "Performance measurement in supply chains: New network analysis and entropic indexes," *International Journal of Production Research*, 48 (8), 2297–2321.

Arunachalam, R., Piya, S., Krishnan, P. K., Muraliraja, R., Christy, J. V., Mourad, A. H. I. and Al-Maharbi, M. (2020), "Optimization of stir–squeeze casting parameters for production of metal matrix composites using a hybrid analytical hierarchy process–Taguchi-Grey approach," *Engineering Optimization*, 52 (7), 1166-1183.

Badri A., Hadi, Seyed H. P. and Xuping W. (2017), "Integrating sustainability into supplier selection with analytical hierarchy process and improved grey relational analysis: a case of telecom industry," *International Journal of Advanced Manufacturing Technology*, 90 (9), 2413–2427.

Bayazit O. (2005), "Use of AHP in decision-making for flexible manufacturing systems," *Journal of Manufacturing Technology Management*, 16 (7), 808–819.

Blecker, T., Kersten, W. and Meyer, C. M. (2005), "Development of an approach for analyzing supply chain complexity," in *Mass customization. concepts–Tools-Realization. Proceedings of the International mass Customization Meeting*, 47–59.

Blome, C., Schoenherr, T. and Eckstein, D. (2014), "The impact of knowledge transfer and complexity on supply chain flexibility: A knowledge-based view," *International Journal of Production Economics*, 147 (B), 307–316.

Bode, C. and Wagner, S. M. (2015), "Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions," *Journal of Operations Management*, 36, 215–228.

Borade, A. B., Kannan, G. and Bansod, S. V. (2013), "Analytical hierarchy process-based framework for VMI adoption," *International Journal of Production Research*, 51 (4), 963-978.

Bozarth, C. C., Warsing, D. P., Flynn, B. B. and Flynn, E. J. (2009), "The impact of supply chain complexity on manufacturing plant performance," *Journal of Operations Management*, 27 (1), 78–93.

Bruno, G., Esposito, E., Genovese, A. and Passaro, R. (2012), "AHP-based approaches for supplier evaluation: Problems and perspectives," *Journal of Purchasing and Supply Management*, 18 (3), 159–172.

Cagliano, A. C., Carlin, A. and Rafele, C. (2009), "Understanding supply chain complexity with performance measurement," in *IFAC Proceedings Volumes (IFAC-PapersOnline)*.

Calinescu, A., Efstathiou, J., Huatuco, L. H. and Sivadasan, S. (2001), "Classes of complexity in manufacturing," in *17th national conference on manufacturing research. , 4–6 September, University of Cardiff*, 351–356.

Chai, J., Liu, J. N and Ngai, E. W. (2013), "Application of decision-making techniques in supplier selection: A systematic review of literature," *Expert Systems with Applications*, 40 (10), 3872–3885.

Chan, J.W.K. (2008), "Product end-of-life options selection: Grey relational analysis approach," *International Journal of Production Research*, 46 (11), 2889–2912.

Chand, P., Thakkar, J. J., & Ghosh, K. K. (2020). "Analysis of supply chain sustainability with supply chain complexity, inter-relationship study using delphi and interpretive structural modeling for Indian mining and earthmoving machinery industry", *Resources Policy*, *68*, 101726.

Chen, F., Drezner, Z., Ryan, J. K. and Simchi-Levi, D. (2000), "Quantifying the bullwhip effect in a simple supply chain: the impact of forecasting, lead times, and information," *Management Science*, 46 (3), 436–443.

Cheng, C. Y., Chen, T. L. and Chen, Y. Y. (2014), "An analysis of the structural complexity of supply chain networks," *Applied Mathematical Modelling*, 38 (9-10), 2328–44.

Choi, T. Y., Dooley, K. J. and Rungtusanatham, M. (2001), "Supply networks and complex adaptive systems: Control versus emergence," *Journal of Operations Management*, 19 (3), 351–366.

Choi, T. Y. and Krause, D. R. (2006), "The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation," *Journal of Operations Management*, 24 (5), 637–652.

Christopher, M. and Holweg, M. (2017), "Supply chain 2.0 revisited: a framework for managing volatility-induced risk in the supply chain," *International Journal of Physical Distribution and Logistics Management*, 47 (1), 2–17.

de Leeuw, S., Grotenhuis, R. and van Goor, A. R. (2013), "Assessing complexity of supply chains: Evidence from wholesalers," *International Journal of Operations and Production Management*, 33 (8), 960–980.

Deshmukh, A. V., Talavage, J. J. and Barash, M. M. (1998), "Complexity in manufacturing systems, Part 1: Analysis of static complexity," *IIE Transactions (Institute of Industrial Engineers)*, 30 (7), 645–655.

Dong, Q. and Cooper, O. (2016), "An orders-of-magnitude AHP supply chain risk assessment framework," *International Journal of Production Economics*, 182, 144–156.

Drzymalski, J. (2015), "A measure of supply chain complexity incorporating virtual arcs," *Journal of Systems Science and Systems Engineering*, 24 (4), 486–499.

Dweiri, F., Kumar, S., Khan, S. A. and Jain, V. (2016), "Designing an integrated AHP based decision support system for supplier selection in automotive industry," *Expert Systems with Applications*, 62, 273–283.

Eckstein, D., Goellner, M., Blome, C. and Henke, M. (2015), "The performance impact of supply chain agility and supply chain adaptability: The moderating effect of product complexity," *International Journal of Production Research*, 53 (10), 3028–3046.

Ellram, L. M. (1991), "Supply Chain Management: The Industrial Organisation Perspedive," *International Journal of Physical Distribution & Logistics Management*, 21 (1), 13–22.

Flynn, B. B. and Flynn, E. J. (1999), "Information-Processing Alternatives for Coping with Manufacturing Environment Complexity," *Decision Sciences*, 30 (4), 1021–1052.

Frizelle, G. and Woodcock, E. (1995), "Measuring complexity as an aid to developing operational strategy," *International Journal of Operations and Production Management*, 15 (5), 26–39.

Goffin, K., Lemke, F. and Szwejczewski, M. (2006), "An exploratory study of 'close' supplier-manufacturer relationships," *Journal of Operations Management*, 24 (2), 189–209.

Govindan, K., Kannan, D. and Haq, A. N. (2010), "Analyzing supplier development criteria for an automobile industry," *Industrial Management and Data Systems*, 110 (1), 43–62.

Grošelj, P., Stirn, L. Z., Ayrilmis, N. and Kuzman, M. K. (2015), "Comparison of some aggregation techniques using group analytic hierarchy process," *Expert Systems with Applications*, 42 (4), 2198–2204.

Gunasekaran, A., Hong, P. and Fujimoto, T. (2014), "Building supply chain system capabilities in the age of global complexity: Emerging theories and practices," *International Journal of Production Economics*.

Gunasekaran, A., Subramanian, N. and Rahman, S. (2015), "Supply chain resilience: Role of complexities and strategies," *International Journal of Production Research*, 53 (22), 6809–6019.

Hamta, N., Shirazi, M. A., Behdad, S. and Ghomi, S. F. (2018), "Modeling and measuring the structural complexity in assembly supply chain networks," *Journal of Intelligent Manufacturing*, 29 (2), 259–275.

Hashemi, A., Butcher, T. and Chhetri, P. (2013), "A modeling framework for the analysis of supply chain complexity using product design and demand characteristics," *International Journal of Engineering, Science and Technology*, 5 (2), 150–164.

Hashemi, S. H., Karimi, A. and Tavana, M. (2015), "An integrated green supplier selection approach with analytic network process and improved Grey relational analysis," *International Journal of Production Economics*, 159, 178–191.

Hesse, M. and Rodrigue, J. P. (2004), "The transport geography of logistics and freight distribution," *Journal of Transport Geography*, 12 (3), 171–184.

Isaai, M. T., Kanani, A., Tootoonchi, M. and Afzali, H. R. (2011), "Intelligent timetable evaluation using fuzzy AHP," *Expert Systems with Applications*, 38 (4), 3718–3723.

Isik, F. (2010), "An entropy-based approach for measuring complexity in supply chains," *International Journal of Production Research*, 48 (12), 3681–3696.

Jacobs, M. A. and Swink, M. (2011), "Product portfolio architectural complexity and operational performance: Incorporating the roles of learning and fixed assets," *Journal of Operations Management*, 29 (7–8), 677–691.

Ju-Long, D. (1982), "Control problems of grey systems," *Systems and Control Letters*, 1 (5), 288–294.

Kannan, V. (2010), "Benchmarking the service quality of ocean container carriers using AHP," *Benchmarking: An International Journal*, 17 (5), 637–656.

Kavilal, E. G., Venkatesan, S. P. and Kumar, K. H. (2017), "An integrated fuzzy approach for prioritizing supply chain complexity drivers of an Indian mining equipment manufacturer," *Resources Policy*, 51 (1), 204–218.

Krishnan, V. and Gupta, S. (2001), "Appropriateness and Impact of Platform-Based Product Development," *Management Science*, 47 (1), 52–68.

Lampón, J. F., Cabanelas, P. and González-Benito, J. (2017), "The impact of modular platforms on automobile manufacturing networks," *Production Planning and Control*, 28 (4), 335–348.

Lee, H. L. and Lee, C. Y. (2007). "*Building supply chain excellence in emerging economies",* Vol. 98, Springer Science & Business Media.

Lee, Y. and Kozar, K. A. (2006), "Investigating the effect of website quality on e-business success: An analytic hierarchy process (AHP) approach," *Decision Support Systems*, 42 (3), 1383–1401.

Li, S., Ragu-Nathan, B., Ragu-Nathan, T. S. and Rao, S. S. (2006), "The impact of supply chain management practices on competitive advantage and organizational performance," *Omega*, 34 (2), 107–124.

Loch, C., Mihm, J. and Huchzermeier, A. (2003), "Concurrent Engineering and Design Oscillations in Complex Engineering Projects," *Concurrent Engineering Research and Applications*, *11*(3), 187-199.

Lucas, R. I., Promentilla, M. A., Ubando, A., Tan, R. G., Aviso, K. and Yu, K. D. (2017), "An AHP-based evaluation method for teacher training workshop on information and communication technology," in *Evaluation and Program Planning*, 93–100.

Luthra, S., Mangla, S. K., Xu, L. and Diabat, A. (2016), "Using AHP to evaluate barriers in adopting sustainable consumption and production initiatives in a supply chain," *International Journal of Production Economics*, 181, 342–149.

Manuj, I. and Sahin, F. (2011), "A model of supply chain and supply chain decision-making complexity," *International Journal of Physical Distribution and Logistics Management*, 41 (5), 511–549.

Min, H. (2010), "Evaluating the comparative service quality of supermarkets using the analytic hierarchy process," *Journal of Services Marketing*, 24 (4), 283–293.

Mohrschladt, R. (2007), "Managing the unexpected in complex chemical supply chains."

Nelabhotla, D. M., Jayaraman, T. V., Asghar, K. and Das, D. (2016), "The optimization of chemical mechanical planarization process-parameters of c-plane gallium-nitride using Taguchi method and grey relational analysis," *Materials and Design*, 104, 392–403.

Nepal, B., Monplaisir, L. and Famuyiwa, O. (2012), "Matching product architecture with supply chain design," *European Journal of Operational Research*, 216 (2), 312–403.

Nivolianitou, Z., Synodinou, B. and Manca, D. (2015), "Flood disaster management with the use of AHP," *International Journal of Multicriteria Decision Making*, 5 (1–2), 152–164.

Pang, Q., Yang, T., Li, M. and Shen, Y. (2017), "A Fuzzy-Grey Multicriteria Decision Making Approach for Green Supplier Selection in Low-Carbon Supply Chain," *Mathematical Problems in Engineering*.

Pathak, S. D., Day, J. M., Nair, A., Sawaya, W. J. and Kristal, M. M. (2007), "Complexity and adaptivity in supply networks: Building supply network theory using a complex adaptive systems perspective", *Decision Sciences*, *38*(4), 547–580.

Perona, M. and Miragliotta, G. (2004), "Complexity management and supply chain performance assessment. A field study and a conceptual framework", *International Journal of Production Economics*, *90*(1), 103–115.

Piya, S. (2019). "Mediator assisted simultaneous negotiations with multiple customers for order acceptance decision", *Benchmarking: An International Journal,* 26(5), 1581-1604.

Piya, S., Khadem, M. M. R. K. and Shamsuzzoha, A. (2016) , "Negotiation based decision support system for order acceptance", *Journal of Manufacturing Technology Management*, *27*(3), 443–468.

Piya, S., Shamsuzzoha, A. and Khadem, M. (2019), "An approach for analysing supply chain complexity drivers through interpretive structural modelling", *International Journal of Logistics: Research and Applications*. https://doi.org/10.1080/13675567.2019.1691514

Piya, S., Shamsuzzoha, A., Khadem, M. and Al-Kindi, M. (2017), "Supply chain complexity drivers and solution methods", *International Journal of Supply Chain Management*, *6*(4), 43–50.

Piya, S., Shamsuzzoha, A., Khadem, M., and Al-Hinai, N. (2020), "Identification of critical factors and their interrelationships to design agile supply chain: Special focus to oil and gas industries", *Global Journal of Flexible Systems Management*, 21, 263-281.

Qureshi, M. N., Kumar, D. and Kumar, P. (2007), "Modeling the logistics outsourcing relationship variables to enhance shippers' productivity and competitiveness in logistical supply chain", *International Journal of Productivity and Performance Management*. https://doi.org/10.1108/17410400710833001

Rajesh, R. and Ravi, V. (2015), "Supplier selection in resilient supply chains: A grey relational analysis approach", *Journal of Cleaner Production*, *86*, 343–359.

Saaty, T. L. (1990), "How to make a decision: The analytic hierarchy process", *European Journal of Operational Research*, *48*(1), 9–26.

Serdarasan, S. (2013), "A review of supply chain complexity drivers", *Computers and Industrial Engineering*, *66*(3), 533–540.

Shah, N. (2005), "Process industry supply chains: Advances and challenges, *Computers and Chemical Engineering"*, *29*(6), 1225-1235.

Shamsuzzoha, A. H. M. and Helo, P. T. (2011), "Information dependencies within product architecture: Prospects of complexity reduction", *Journal of Manufacturing Technology Management*, *22*(3), 314–329.

Sharma, M. J., Moon, I. and Bae, H. (2008), "Analytic hierarchy process to assess and optimize distribution network", *Applied Mathematics and Computation*, *202*(1), 256–265.

Sharma, S. and Dubey, D. (2010), "Multiple sourcing decisions using integrated AHP and knapsack model: A case on carton sourcing", *International Journal of Advanced Manufacturing Technology*, *51*(9–12), 1171–1178.

Shinde, A. B. and Pawar, P. M. (2017), "Multi-objective optimization of surface textured journal bearing by Taguchi based Grey relational analysis", *Tribology International*, *114*, 349–357.

Shou, Y., Li, Y., Park, Y. W., & Kang, M. (2017). The impact of product complexity and variety on supply chain integration. *International Journal of Physical Distribution & Logistics Management*, *47*(4), 297-317.

Sivadasan, S., Efstathiou, J., Frizelle, G., Shirazi, R. and Calinescu, A. (2002), "An information-theoretic methodology for measuring the operational complexity of supplier-customer systems", *International Journal of Operations and Production Management*, *22*(1), 80–102.

Sivadasan, S., Smart, J., Huaccho Huatuco, L. and Calinescu, A. (2010), "Operational complexity and supplier-customer integration: Case study insights and complexity rebound", *Journal of the Operational Research Society*, *61*(12), 1709–1718.

Stadtler, H. (2015), "Supply Chain Management: An Overview", (pp. 3–28) Berlin Heidelberg: Springer. https://doi.org/10.1007/978-3-642-55309-7_1

Suh, N. P. (2005), "Complexity in engineering", *CIRP Annals - Manufacturing Technology*, *54*(2), 46–63.

Sun, G., Guan, X., Yi, X. and Zhou, Z. (2018), "Grey relational analysis between hesitant fuzzy sets with applications to pattern recognition", *Expert Systems with Applications*, *92*, 521–532.

Triki, C., Mirmohammadsadeghi, S. and Piya, S. (2017), "Heuristic methods for the periodic Shipper Lane Selection Problem in transportation auctions", *Computers and Industrial Engineering*, *106*, 182-191.

Triki, C., Piya, S. and Fu, L. (2020), "Integrating production scheduling and transportation procurement through combinatorial auctions", *Networks*, 76 (2), 147-163.

Turner, N., Aitken, J. and Bozarth, C. (2018), "A framework for understanding managerial responses to supply chain complexity", *International Journal of Operations and Production Management*, *38*(6), 1433–1466.

Ulloa, C., Nuñez, J. M., Lin, C. and Rey, G. (2018), "AHP-based design method of a lightweight, portable and flexible air-based PV-T module for UAV shelter hangars", *Renewable Energy*, *123*, 767–780.

Vachon, S. and Klassen, R. D. (2002), "An exploratory investigation of the effects of supply chain complexity on delivery performance", *IEEE Transactions on Engineering Management*, *49*(3), 218-230.

Vinodh, S., Madhyasta, U. R. and Praveen, T. (2012), "Scoring and multi-grade fuzzy assessment of agility in an Indian electric automotive car manufacturing organisation", *International Journal of Production Research*, *50*(3), 647-660.

Wang, H., Gu, T., Jin, M., Zhao, R., & Wang, G. (2018). The complexity measurement and evolution analysis of supply chain network under disruption risks. *Chaos, Solitons & Fractals*, *116*, 72-78.

Wei, Y., Chen, F. and Xiong, F. (2018), "Dynamic complexities in a supply chain system with lateral transshipments", *Complexity*. https://doi.org/10.1155/2018/3959141

Wilding, R. (1998), "The supply chain complexity triangle: Uncertainty generation in the supply chain", *International Journal of Physical Distribution & Logistics Management*, *28*(8), 599–616.

Wong, C. W. Y., Lai, K. H. and Bernroider, E. W. N. (2015), "The performance of contingencies of supply chain information integration: The roles of product and market complexity", *International Journal of Production Economics*, *165*, 1–11.

Wu, Z. and Choi, T. Y. (2005), "Supplier-supplier relationships in the buyer-supplier triad:

Building theories from eight case studies", *Journal of Operations Management*, *24*(1), 27–52.

Xuerui, T. and Yuguang, L. (2004), "Using grey relational analysis to analyze the medical data", *Kybernetes* (pp. 355–362).

Yang, C. C. and Chen, B. S. (2006), "Supplier selection using combined analytical hierarchy process and grey relational analysis", *Journal of Manufacturing Technology Management*, *17*(7), 926–941.

Yang, J. (2009), "Integrative performance evaluation for supply chain system based on logarithm triangular fuzzy number-AHP method", *Kybernetes*, *38*(10), 1760–1770.

Zhou, S., Zhou, L., Yu, L., Liu, S., Luo, Q., Sun, P. and Wu, J. (2016), "Monitoring chip fatigue in an IGBT module based on grey relational analysis", *Microelectronics Reliability*, *56*, 49–52.

Appendix A: Questionnaire

This survey is to check the SC complexity level of your esteemed company. The SC complexity level is defined in terms of five dimensions such as "strategic management", "production planning and control", "supplier base", "marketing and sales", and "information and communication". Each dimension is further defined by means of various drivers based on which the following questionnaires have been designed. Each question in the survey has five subjective answers. Please select any one of the available options that best suits for your esteemed company.

1. Strategic Management

m11. How stable is your organizational structure? Is the structure flexible enough to accommodate the changes according to the need?	○ Not at all ○ High	○ Poor ○ Very high	○ Medium
m12. How efficient and effective is your R&D facility and product development unit?	○ Not at all ○ High	○ Poor ○ Very high	○ Medium
m13. How often technological innovation, incremental as well as disruptive, in the field of your product is occurring?	○ Very less ○ High	○ Less ○ Very high	○ Medium
m14. Does the product need to acquire various standards in order to be competitive in the market?	○ Very less ○ Much	○ Less ○ Very much	○ Medium
m15. How often your company/ product is facing legal hurdles at various jurisdiction, where it operates and how difficult is it for the company to satisfy government regulations?	○ Very less ○ Frequent	○ Less ○ Very frequent	○ Medium

2. Production planning and control

m21. How many varieties of same product types do your company produces?	⬭ Very less ⬭ High	⬭ Less ⬭ Very high	⬭ Medium
m22. How robust is your manufacturing process, including state-of-the art manufacturing facility?	⬭ Not at all ⬭ High	⬭ Poor ⬭ Very high	⬭ Medium
m23. How often does your production plan changes due to inability of the system to adhere to the production schedule?	⬭ Very less ⬭ Frequent	⬭ Less ⬭ Very frequent	⬭ Medium
m24. How often the production system is disrupted due to the constraint of resources within the supply chain network?	⬭ Very less ⬭ Frequent	⬭ Less ⬭ Very frequent	⬭ Medium
m25. How robust is your logistics and transportation network, including multi-modal transportation system?	⬭ Very less ⬭ High	⬭ Less ⬭ Very high	⬭ Medium

3. Supplier base

m31. How well your process is synchronized with supply chain partners and how good is your monitoring system to monitor the progress at suppliers' locations?	⬭ Very poor ⬭ Good	⬭ Poor ⬭ Very good	⬭ Medium
m32. How many supply chain partners do your company have?	⬭ Very less ⬭ Much	⬭ Less ⬭ Very much	⬭ Medium
m33. How far your suppliers are located?	⬭ Very close ⬭ Far	⬭ Close ⬭ Very far	⬭ Medium
m34. How compatible is your company culture with respect to your suppliers?	⬭ Very low ⬭ High	⬭ Low ⬭ Very high	⬭ Medium
m35. How compatible is your supply chain network?	⬭ Very less ⬭ High	⬭ Less ⬭ Very high	⬭ Medium

4. Marketing and sales

m41. How effective is your marketing and how sales strategy?	⬭ Very less ⬭ Effective	⬭ Less ⬭ Very effective	⬭ Medium
m42. How often the customer needs change to the product domain of your company?	⬭ Very less ⬭ Often	⬭ Less ⬭ Quite often	⬭ Medium
m43. How many competitors your product has?	⬭ Very less ⬭ Much	⬭ Less ⬭ Very much	⬭ Medium
m44. How many categories of customers do your company have?	⬭ Very less ⬭ High	⬭ Less ⬭ Very high	⬭ Medium

5. Information and Communication

m51. How effective is your inter-departmental communications and information sharing?	○ Very less ○ Effective	○ Less ○ Very effective	○ Medium
m52. How severe is the forecasting error due to improper information sharing among supply chain member?	○ Very less ○ Severe	○ Less ○ Very severe	○ Medium
m53. How compatible is the information technology used by all the members in your supply chain network?	○ Very less ○ High	○ Less ○ Very high	○ Medium