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Evaluation of supply chain coordination index in context to Industry 4.0 environment

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Abstract

Purpose – Today, most of the manufacturing systems are changing very fast in terms of the adoption of new technologies. New technologies being implemented are Internet of Things, cyber physical systems, cloud computing, Big Data analytics and information and communication technologies. Most of the organizations in the value chain are implementing these technologies at the individual level rather than across the whole supply chain. It makes the supply chain less coordinated and causes suboptimal utilization of resources. For efficient and optimal use of modern technologies, supply chains should be highly coordinated. The purpose of this paper is to illustrate an approach for determining the index to quantify coordination in the supply chain.
Design/methodology/approach – From the literature review, total 32 factors have been identified. These factors are further clubbed into six clusters for evaluation of the coordination index. The graph theoretic approach has been used for evaluating the coordination index of a supply chain of an Indian organization.
Findings – This study has illustrated a comprehensive approach to quantify coordination of a supply chains for effective benchmarking of the supply chain performance in the Industry 4.0 era. Presently, it is observed that top management is giving more focus on organizational issues such as lean organization structure, organization culture and responsiveness factors for improving coordination in the supply chain rather than on Industry 4.0 technologies.
Originality/value – This framework can also be used for comparison, ranking and analysis of coordination issues in different supply chains in the era of Industry 4.0. Organizations can use this approach for benchmarking purpose also to improve different supply chain processes for meeting dynamic market requirements.

Keywords Benchmarking, Coordination, Supply chain management, Industry 4.0, Intelligent manufacturing, Graph theoretic approach
Paper type Research paper

1. Introduction

In the present context of a globalized market, manufacturing organizations are designing their operations based on changing customer needs (Gunasekaran, 2005). Organizations are trying to fulfill the continuously changing market requirements in terms of reducing lead time, variety of products, flexible manufacturing systems, etc. (Stock and Seliger, 2016). Internet of Things (IOTs), 3D printing, data analytics, artificial intelligence and cloud computing (Almada-Lobo, 2016) are some of the modern technologies implemented by managers in different manufacturing processes to become competitive. Supply chain management (SCM) definition has been transformed in comparison to traditional SCM definition (Tjahjono *et al.*, 2017) due to the use of these new technologies. In 2011, Hanover Messe introduced the concept of "Industry 4.0."

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Industry 4.0 can be defined as the "smart manufacturing" or "integrated industry." According to Hofmann and Rüsch (2017), Industry 4.0 has potential to change the whole business in terms of product designing, manufacturing and delivery. Industry 4.0 helps in creating efficient production systems. Wang *et al.* (2016) observed that production systems can make quick decisions and monitor physical processes in the era of Industry 4.0 through real-time transmissions with humans, machines and sensors. It may also be termed as "Intelligent manufacturing." According to Kaushik (1990), the purpose of intelligent manufacturing is to optimize the resources by using advanced information and manufacturing technologies. In intelligent manufacturing, processes related to design, production and product life cycle management are continuously upgraded. Adaptive decision-making models, advanced materials, intelligent devices, smart sensors and data analytics are used to manage the product life cycle (Li *et al.*, 2017). It further improves performance and service levels (Davis *et al.*, 2012). Therefore, Industry 4.0 comprises highly developed automation and digitization of processes. Major requirements for Industry 4.0 to be interoperable are accessibility, multilingualism, security, privacy, subsidiarity, the use of open standards, open source software and multilateral solutions (Hermann *et al.*, 2016). Industry 4.0 makes factories more intelligent, flexible and dynamic by equipping manufacturing with sensors, actors and autonomous systems.

According to Van Hoek and Chapman, (2007), supply chains have become highly unpredictable due to increased product variety and shortening product life cycle. Zhang *et al.* (2016) observed that in the supply chain, the elimination of non-value-added activities and coordination are essential for bringing agility. Coordination in the supply chain means integration of all processes to ensure sharing of information, managing relationship, technology transfer and application of latest technologies such as IOTs, Industry 4.0 and cloud computing for the efficient management of supply chain operations. To assess the effectiveness of coordination in the supply chain, quality of product, innovation and customer satisfaction are major factors. Main factors involved in achieving coordination among members of the supply chain are human and resource development; applications of modern technologies and IT tools; development of effective strategies; sharing of profits and risks.

Most researchers have focused on the importance of coordination in a traditional supply chain but very limited research is available for developing the index to evaluate the effectiveness of coordination in context to supply chain in the era of Industry 4.0. Mainly researchers have used popular models such as Balance Score card, SCOR model, etc., for performance evaluation. The authors are of the opinion that performance can be improved only after ensuring coordination in the supply chain in the Industry 4.0 environment. These models can be further improved by making them more inclusive in terms of modern supply chains in the Industry 4.0 era. Most of the supply chains are not only struggling to ensure coordination in the Industry 4.0 environment but are also unable to measure it effectively. Therefore, the objectives of this study are:

- to identify major factors for coordination in supply chains; and
- to develop a framework for evaluating coordination effectiveness in Industry 4.0-based supply chains.

The remaining part of the paper is organized as follows: Section 2 studies the literature review for coordination factors; Section 3 explains different steps of graph theoretic approach with a case illustration and Section 4 talks about conclusion.

2. Literature review

In the era of Industry 4.0, supply chains are more technology based. Major technologies being used in different functions of supply chains are IOTs, Big Data analytics, cloud computing, artificial intelligence, machine learning, etc. Automation of different processes across the supply chain is essential for survival in the new business environment. It is very important to have coordination among the members of the value chain for the integration of different supply chain functions (Soroor *et al.*, 2009). Manufacturing flexibility is the most important factor for being competitive (Singh and Sharma, 2014). For improving manufacturing flexibility, the coordinated supply chain is very crucial. Supply chain members need to be coordinated by efficiently managing dependencies between each other (Arshinder *et al.*, 2009). In a coordinated supply chain, the emphasis has been given to supplier–buyer relationship (Jain *et al.*, 2009). According to Lee (2000), the supply chain integration is due to organizational relationship, logistics coordination and information sharing. According to Melnyk *et al.* (2009), the supply chain is changing from tactical to strategic nature. Future supply chain will be more complex and demanding. Hsu *et al.* (2009) analyzed that the practices of SCM mediate the relationship between operations capability and firm performance.

The factors of coordination in the supply chain are analyzed based on the literature review and are grouped further into six clusters. These are discussed in the following section.

2.1 C1: top management commitment

The important variable for successful supply chain strategies is the top management commitment (Sun *et al.*, 2009; Skipworth *et al.*, 2015). Top management commitment helps organizations to go for the major decisions like investment of time and money for resources development (Shin *et al.*, 2000). It also helps in long-term goal for investment (Arshinder *et al.*, 2006), adoption of new technology (Arshinder *et al.*, 2006), better-focused communication system and employee training and empowerment (Simatupang *et al.*, 2002). In changing the business environment, the role of top management commitment has been emphasized as effective SCM (Sandberg and Abrahamsson, 2010). Singh *et al.* (2004) also observed in context to Indian SMEs that the top management support is essential for implementing new initiatives.

2.2 C2: organizational factors

Under dynamic market conditions, organizations are trying to make themselves more proactive for changes. Singh *et al.* (2004) observed that in many organizations, the parts are delivered by suppliers several times a day to the assembly lines directly without maintaining any big inventory. Lead time for replenishment and for customers is continuously decreasing. Organizational factors such as lean organization structure (Grittell and Weiss, 2004), JIT and lean practices (Arshinder *et al.*, 2006), organization culture for supply chain implementation and integration within the organization departments (Grittell and Weiss, 2004) are important for better coordination of the supply chain.

2.3 C3: mutual understanding

To ensure effective revenue and risk sharing among partners of the supply chain, mutual understanding is essential (Singh, 2013). Chopra and Meindle (2003) observed that trust is a favorable attitude for supply chain members to have confidence on each other. Conflicts of interest may occur when the existing revenue sharing system promotes for individual interest in place of whole supply chain interest (Cachon and Lariviere, 2005). Bianchi and Saleh (2010) observed that in developing countries, trust and commitment are essential for enhancing the performance of the supply chain. Arshinder *et al.* (2007) observed that the members of the supply chain need to have common goals and objectives for global optimization.

2.4 C4: flow of information

Embedded production system technologies with intelligent manufacturing processes are combined through Industry 4.0. It has potential to transform traditional supply chains into advanced IT-enabled supply chain. Manufacturing systems need to be continuously upgraded in the context of Industry 4.0 environment. Intelligent manufacturing may make organizations smart, flexible and capable to meet dynamic market requirements (Shen and Norrie, 1999). Wan *et al.* (2017) observed that Industry 4.0 technologies can make organization agile and responsive.

Pyke *et al.* (2000) emphasized on information and knowledge sharing in the supply chain. The availability of real-time sales data is important for effective inventory management (Michelino *et al.*, 2008). The inventory cost at every stage of the supply chain is reduced by managing inventory efficiently (Marek and Malyszek, 2008). Stanley *et al.*, (2009) observed that responsiveness gets improved through information sharing among the supply chain members. Sharing of different operational issues such as inventory, market demand and product performance in the market are related to information sharing.

2.5 C5: relationship and decision making

Long-term relationship and collaborative decision making among the members of the supply chain are essential for streamlining the supply chain functions in the era of Industry 4.0. It also increases the mutual trust between the supply chain members and flow of information (Mehrjerdi, 2009). The store-level retailer's replenishment problem was analyzed and the collaborative replenishment mechanism model was proposed by Lyu *et al.* (2010). In supply chains, the important factors for relationship and decision-making are logistic synchronization (Simatupang *et al.*, 2002), rationalization of suppliers (Jain *et al.*, 2009) and supply chain integration (Arshinder *et al.*, 2006).

2.6 C6: responsiveness

According to Kim *et al.*, (2006), the responsiveness of a supply chain means how quickly it is able to react to market requirements. Moller (2006) observed that collaborative efforts of supply chain partners improve supply chain responsiveness. Agility in operations is an important factor for a responsive supply chain (Li *et al.*, 2008). Flexibility in the production system (Koh *et al.*, 2007), delivery on time (Mehrjerdi, 2009), service reliability (Konijnendijk, 1994) and ability to adopt process change (Li *et al.*, 2008) are major ingredients of the responsive supply chain. Differences in the goals and objectives among supply chain members lead to the local optimization of the whole supply chain (Arshinder *et al.*, 2007). Michelino *et al.* (2008) observed that the availability of point of sales data is important for improving the responsiveness of the supply chain. Delivery in time, cost reduction and accurate forecasting of data are ensured by the responsive supply chain (Mehrjerdi, 2009). Coordination in the supply chain helps in cost reduction (Hult *et al.*, 2002), improved product quality (Handfield, 1994) and better process design (Tan, 2002). Product and process design impacts the responsiveness of the supply chain (Khan *et al.*, 2012).

Based on the literature review, total 32 sub-factors have been identified and further grouped into six clusters. These are summarized in Table I.

3. Research methodology

Based on the literature review, 32 factors impacting coordination in the supply chains are identified. For validating the inclusion of these factors, in addition to the literature review, the opinion of experts was also considered. Based on the focused group discussion, these factors were categorized into six categories. To quantify coordination in the supply chain, the graph theoretic approach is used. Detailed steps are described in the following section.

3.1 Graph theoretic (digraph) approach

Diagraph representation, the matrix representation and the permanent function representation are the parts of the graph theoretical approach. Different factors with their mutual relationships are visually represented in the digraph. Index is determined by the

Table I. Factors for coordination in the supply chain

S. No.	Factors of coordination in supply chain	References
1	Top management commitment (*C*1)	
	(a) Investment of time and money for recourses development	Shin *et al.* (2000), Kumar *et al.* (2014), Skipworth *et al.* (2015), Kumar and Singh (2017)
	(b) Focused communication system	Kim and Narsimhan (2002), Stank *et al.*(1999)
	(c) Long-term investment motive	Arshinder *et al.* (2006), Skipworth *et al.* (2015)
	(d) Commitment to promises	Singh *et al.* (2010)
	(e) Ready to adopt new technology	Arshinder *et al.* (2006), Stanley *et al.* (2009), Zhang *et al.* (2016), Kumar and Singh (2017)
	(f) Employees training and empowerment	Simatupang *et al.* (2002)
2	Organizational factors (*C*2)	
	(a) Lean organization structure	Grittell and Weiss (2004), Zhang *et al.* (2016)
	(b) JIT and lean practices	Arshinder *et al.* (2006), Grittell and Weiss (2004)
	(c) Organization behavior for supply chain implementation	Arshinder *et al.* (2006), Grittell and Weiss (2004), Kumar and Singh (2017)
	(d) Organization culture for supply chain Implementation	Arshinder *et al.* (2006), Grittell and Weiss (2004)
	(e) Role in the supply chain with respect to other members	Freathy and O'Connell (1998)
	(f) Integration of departments within the organization	Grittell and Weiss (2004), Kumar *et al.* (2013), Kumar and Singh (2017)
3	Mutual understanding (*C*3)	
	(a) Agreed vision and goals of the members of the supply chain	Arshinder *et al.* (2006), Simatupang *et al.* (2002)
	(b) Trust development in supply chain members	Arshinder *et al.* (2006), Sahay (2003), Bianchi and Saleh, (2010), Zhang *et al.* (2016)
	(c) Effective implementation of joint replenishment and forecasting decisions	Arshinder *et al.* (2006)
	(d) Supply chain risk/reward sharing	Cachon and Lariviere (2005), Lee (2000), Kumar and Singh (2017)
4	Flow of information (*C*4)	
	(a) Usage of information technology (IT) tools and techniques	Simatugang and Sridharan (2002), Leeand Lee (2010)
	(b) Information sharing/exchange	Arshinder *et al.* (2009), Kumar and Singh (2017), Ozer(2003), Stanley *et al.* (2009)
	(c) Inventory tracking at supply chain linkage	Mentzer *et al.* (2001)
	(d) Data sharing related to purchasing and supplies	Simatugang and Sridharan (2002)
	(e) Knowledge sharing	Pyke *et al.* (2000), Simatupang *et al.* (2002)
	(f) Design data sharing	Kumar *et al.* (2017)
5	Relationship and decision making (*C*5)	
	(a) Long-term relationship with suppliers	Jain *et al.* (2009), Olorunniwo and Hartfield (2001)
	(b) Long-term relationship with customers	Jain *et al.* (2009), Olorunniwo and Hartfield (2001), Agrawal *et al.* (2016a, b)
	(c) Collaborative decision making/planning with supply chain members	Tsay (1999), Cachon and Fisher (2000), Disney and Towill (2003), Lyu *et al.* (2010)
	(d) Logistics synchronization	Simatupang and Sridharan (2002), Simatupang *et al.* (2002)
	(e) Supply chain integration	Arshinder *et al.* (2006), Lee (2000), Villa (2002), Chan *et al.* (2004)
	(f) Rationalization of suppliers	Jain *et al.* (2009)
6	Responsiveness (*C*6)	
	(a) Flexibility in the production system	Koh *et al.* (2007), Arshinder *et al.* (2006), Kumar *et al.* (2017), Singh (2015)
	(b) Delivery on time	Lee and Lee (2010), Mehrjerdi, (2009)
	(c) Service reliability	Konijnendijk (1994), Kumar and Singh (2017)
	(d) Ability to adopt process change	Li *et al.* (2008)

permanent function of the matrix. Grover *et al.* (2004) used this approach in the area of total quality management. Agrawal *et al.* (2016a, b) used this approach for outsourcing decisions in reverse logistics. This approach was used in an automotive organization to evaluate the agility index (Kumar *et al.*, 2017).

The level of coordination in terms of a single numerical index (per C^*) can be evaluated using the graph theoretic approach which is given as below:

$$\text{Coordination index} = \text{per } C^* = f \text{ (main factors and their sub} - \text{factors)}.$$

The coordination index for the supply chain of an organization is found using the methodology presented in this paper. By comparing the coordination index for different supply chains, we can find weak links for further improvement. It is a versatile methodology, which can be used to find the supply chain coordination index in the era of Industry 4.0. The effect of factors and their interdependencies are taken into consideration in this analysis. The proposed methodology involves various steps which are:

(1) different factors for coordination in the supply chain are identified;

(2) categorize these factors into six clusters;

(3) a digraph among the clusters is developed depending on their mutual interactions (as shown in Figure 1);

(4) determine the interaction of different factors;

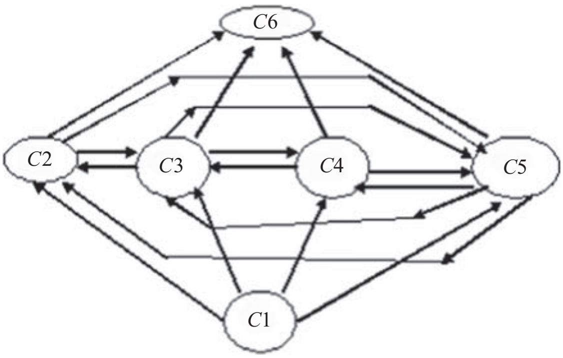
(5) develop a variable permanent matrix (VPM) at the system level based on the digraph developed in Step 3; and

(6) find the variable permanent function (VPF) using Equation (9).

For the absolute measure of factors, a scale from 1 to 9 has been used (1 – exceptionally low, 2 – very low, 9 – exceptionally high.). For the relative measure of interdependencies of factors, a scale from 1 to 5 is used (1 – very weak, 5 – very strong).

Above mentioned steps are applied to calculate the coordination index for a supply chain of an organization in the following section.

3.1.1 Cluster digraph. In the supply chain, digraph for clusters is prepared to represent coordination dynamics in terms of nodes and edges. Clusters/factors are represented by nodes, whereas their mutual interactions are represented by edges. C_i indicates the absolute



Note: $C1$ – top management commitment, $C2$ – organizational factors, $C3$ – mutual understanding, $C4$ – flow of information, $C5$ – relationship and decision making, $C6$ – responsiveness

Figure 1. Digraph for clusters of enablers for coordination in the supply chain

importance of factors and c_{ij} indicates the relative importance of jth factor on ith factor based on mutual interaction. A directed edge from node i to node j is represented by c_{ij} in the digraph. The proposed clusters of factors and their interactions are shown by the digraph. Top management commitment ($C1$), organizational factors ($C2$), mutual understanding ($C3$), flow of information ($C4$), relationship and decision making ($C5$) and responsiveness ($C6$) are identified as clusters and interactions amongst them are shown in the form of diagraph (Figure 1). A team of five experts was formed having more than 10 years of experience in the area of SCM. These had three experts from industry and two from academia.

3.1.2 Clusters matrix (Em). An expression for factor's effect is established by representing the digraph in the matrix form. In general case, if n factors are leading to nth order symmetric (0, 1) then matrix A=[C_{ij}]. The value of C_{ij} represents the interaction of ith factor with that of the jth factor:

$$C_{ij} = 1 \text{ if factor } i \text{ is linked to factor } j; = 0 \text{ otherwise.}$$

Generally, C_{ij}, the factor's effect is directional and if $C_{ii} = 0$ then factors are not interacting with itself. For coordination in the supply chain, six clusters of factors have been made (Figure 1) in this study. The digraph represented by factor's matrix as shown in Figure 1 is written as:

$$A = \begin{array}{c} \begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 \end{matrix} \\ \begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}_{6\times 6} \end{array} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{matrix} \tag{1}$$

The interdependency of enablers is represented by the off-diagonal elements having value 0 or 1. In factor's matrix, if the effect of factors is not taken into consideration then the diagonal elements are 0. For this another matrix named factor's characteristic matrix is defined by B.

3.1.3 Clusters characteristic matrix. The characteristic matrix which is used in mathematics is also used to characterize factors affecting coordination in the supply chain. Enablers characteristic matrix is written as B=[CI−A], where I is an identity matrix; C is a variable representing enabler and A is the same as in Equation (1):

$$I = \begin{array}{c} \begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 \end{matrix} \\ \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}_{6\times 6} \end{array} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{matrix} \tag{2}$$

$$
CI = \begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & \\ \begin{pmatrix} C & 0 & 0 & 0 & 0 & 0 \\ 0 & C & 0 & 0 & 0 & 0 \\ 0 & 0 & C & 0 & 0 & 0 \\ 0 & 0 & 0 & C & 0 & 0 \\ 0 & 0 & 0 & 0 & C & 0 \\ 0 & 0 & 0 & 0 & 0 & C \end{pmatrix}_{6\times6} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \quad (3)
$$

$$
B = [CI - A] = \begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & \\ \begin{pmatrix} C & -1 & -1 & -1 & -1 & -1 \\ 0 & C & -1 & -1 & -1 & -1 \\ 0 & -1 & C & -1 & -1 & -1 \\ 0 & -1 & -1 & C & -1 & -1 \\ 0 & -1 & -1 & -1 & C & -1 \\ 0 & 0 & 0 & 0 & 0 & C \end{pmatrix}_{6\times6} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \quad (4)
$$

The value of all diagonal elements in the above matrix is the same which means that all the factors have been assigned the same value. This is practically not true as all factors have different values (effects) based on various parameters affecting them. Depending on mutual relationship the values have been assigned to interdependencies. Variable characteristic matrix (VCM), i.e. R, is considered to see the effect of factors and their interdependencies.

3.1.4 Variable characteristic matrix. The VCM is used for various factors and their effects to characterize the coordination in the supply chain. For this, a digraph (Figure 1) is considered to define the factors' VCM. A matrix D is considered having off-diagonal elements C_{ij} which shows interactions between factors, i.e. instead of 1 (as in matrix 1). Another matrix E is considered with diagonal elements C_i, $i=1, 2, \ldots, 6$, where C_i represents the effect of various factors, i.e. instead of C only (as in matrix 3).

The factors' VCM is written as R=[E−D] by considering matrices D and E:

$$
D = \begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & \\ \begin{pmatrix} 0 & C12 & C13 & C14 & C15 & C16 \\ 0 & 0 & C23 & C24 & C25 & C26 \\ 0 & C32 & 0 & C34 & C35 & C36 \\ 0 & C42 & C43 & 0 & C45 & C46 \\ 0 & C52 & C53 & C54 & 0 & C56 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}_{6\times6} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \quad (5)
$$

$$E = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\ \begin{pmatrix} C1 & 0 & 0 & 0 & 0 & 0 \\ 0 & C2 & 0 & 0 & 0 & 0 \\ 0 & 0 & C3 & 0 & 0 & 0 \\ 0 & 0 & 0 & C4 & 0 & 0 \\ 0 & 0 & 0 & 0 & C5 & 0 \\ 0 & 0 & 0 & 0 & 0 & C6 \end{pmatrix}_{6\times 6} \end{array} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \quad (6)$$

$$R = [E - D] = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\ \begin{pmatrix} C1 & -C12 & -C13 & -C14 & -C15 & -C16 \\ 0 & C2 & -C23 & -C24 & -C25 & -C26 \\ 0 & -C32 & C3 & -C34 & -C35 & -C36 \\ 0 & -C42 & -C43 & C4 & -C45 & -C46 \\ 0 & -C52 & -C53 & -C54 & C5 & -C56 \\ 0 & 0 & 0 & 0 & 0 & C6 \end{pmatrix}_{6\times 6} \end{array} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \quad (7)$$

Some of the coefficients of the determinant for matrix Equation (7) possess positive and negative signs. Hence, complete information on factors' effect will not be obtained as some will be lost due to the addition and subtraction of the numerical values of diagonal and off-diagonal elements (i.e. C_i and C_{ij}). The complete information about factor's effect is not given by the determinant of matrix Equation (7). Hence, another matrix is introduced named VPM.

3.1.5 Variable permanent matrix. Of all the factors if the value of the individual effect is maximum then the overall factors' effect is also maximum. In the VCM as the total quantitative information is not obtained, so the VPM in general is defined for the system considering interactions among all factors as:

$$C^* = [E + D] = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\ \begin{pmatrix} C1 & C12 & C13 & C14 & C15 & C16 \\ 0 & C2 & C23 & C24 & C25 & C26 \\ 0 & C32 & C3 & C34 & C35 & C36 \\ 0 & C42 & C43 & C4 & C45 & C46 \\ 0 & C52 & C53 & C54 & C5 & C56 \\ 0 & 0 & 0 & 0 & 0 & C6 \end{pmatrix}_{6\times 6} \end{array} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \quad (8)$$

E and D have the same meaning as described in matrix Equations (5) and (6), respectively. VPF which is also called permanent of C (per C) is the permanent of matrix Equation (8) which is multinomial. This is calculated by standard procedures same as that of the determinant of factors' VCM but with all positive signs. In a general form, the permanent for matrix Equation (8) is written as:

$$
\begin{aligned}
\mathrm{VPM} = \mathrm{VPF} = \operatorname{per} C* = & \prod_{i=1} C_i + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji})C_kC_lC_mC_n \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{jk}C_{ki} + C_{ik}C_{kj}C_{ji})C_lC_mC_n \\
& + \Bigg[\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji})(C_{kl}C_{lk})C_mC_n \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{jk}C_{kl}C_{li} + C_{il}C_{lk}C_{kj}C_{ji})C_mC_n)\Bigg] \\
& + \Bigg[\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji})(C_{kl}C_{lm}C_{mk} + C_{km}C_{ml}C_{lk})C_n \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji}C_{kl}C_{lm}C_{mi} + C_{im}C_{ml}C_{lk}C_{ki}C_{ji})C_n\Bigg] \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji}C_{kl}C_{lm}C_{mi} + C_{im}C_{ml}C_{lk}C_{ki}C_{ji})C_n] \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji})(C_{kl}C_{lm}C_{mn}C_{nk} + C_{kn}C_{nm}C_{ml}C_{lk}) \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{jk}C_{ki})(C_{lm}C_{mn}C_{nl}) \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji})(C_{lk}C_{kl})(C_{mn}C_{nm}) \\
& \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (C_{ij}C_{ji}C_{kl}C_{lm}C_{mi} + C_{im}C_{ml}C_{lk}C_{ki}C_{ji})].
\end{aligned} \tag{9}
$$

The above defined permanent function which is Equation (9) expresses the factors' effect due to the presence of all attributes and their interdependencies. A close look at multinomial, i.e. Equation (9), reveals the presence of factors' effect in a systematic manner. The terms in this expression are arranged in $n+1$ grouping. Seven grouping are there as n=6.

3.1.6 Case illustration. The organization chosen for this case study is ABC Ltd (name changed), the member of automotive component manufacturers association of India. It was established in 1989. It is ISO9001 certified organization. It has an annual turnover of Rs 110m US$. It manufactures a variety of auto components and electric switches for two wheelers and four wheelers like combination switch, horns, etc. The supply chain of the organization consists of customers such as Hero Honda, Maruti Udyog Ltd, General Motors, TVS, Honda Motors Cycles and Scooter, etc., and different vendors, distributors and organization itself.

The organization was facing problems from the last few years due to poor coordination among the members of the supply chain. Major problems faced by this organization are increasing inventory cost, lack of information flow, not able to deliver all products on time. So there was a need of study coordination issues of its supply chain. The authors made three visits to discuss supply chain coordination issues with management. The sample of study includes supply chain managers, top management members, marketing and vendor development managers. To select the true representative sample of population, the professionals were selected from all levels of management. The sample was drawn from the managers, who were directly and indirectly involved in coordination with other members of the supply chain. For survey two well-structured, a multi-choice questionnaire was sent to professionals of the organization. Major clusters and sub-factors are shown in Figure 1. The first questionnaire was designed for collecting response on the importance of six main clusters ($C1$–$C6$). The second questionnaire was prepared for finding the influence of clusters on each other, i.e. C12 means the influence of top management commitment ($C1$) on organizational factors ($C2$); similarly, C23 means the influence of organizational factors ($C2$) on mutual understanding ($C3$).

From the questionnaire-based study, we will get the values of the following variables as used in Equation (8), i.e. VPM:

$$C1,\ C12,\ C13,\ C14,\ C15,\ C16,\ C2,\ C23,\ C24,\ C25,\ C26,\ C32,\ C3,\ C34,$$

$$C35,\ C36\ C42,\ C43,\ C4,\ C45,\ C46,\ C52,\ C53,\ C54,\ C5,\ C56,\ C6.$$

We considered a team of five experts from the top- and mid-level management of this organization for taking the response on different dimensions of coordination. Values of the above variables coming from the response given by senior- and mid-level managers of the organization are given as follows:

$$\begin{array}{lllll} C1 = 4.5,\ C12 = 3,\ C13 = 3,\ C14 = 4, & & & C15 = 3, & C16 = 4 \\ C2 = 4.5, & C23 = 3, & C24 = 4, & C25 = 3, & C26 = 4 \\ C32 = 3, & C3 = 4.5, & C34 = 2, & C35 = 3, & C36 = 4 \\ C42 = 5, & C43 = 5, & C4 = 2.06, & C45 = 5, & C46 = 5 \\ C52 = 3, & C53 = 3, & C54 = 3, & C5 = 3.02, & C56 = 3 \\ C6 = 4.5 & & & & \end{array}$$

Putting these values in Equation (9) for solution and find the value of per C^*. It is found as given below:

$$\text{Per } C^* = 70{,}236.$$

This is the index for coordination in the supply chain of the company ABC Pvt Ltd. It is observed that presently for improving coordination in the supply chain, top management ($C1$) is giving more focus on organizational factors ($C2$) such as lean organization structure, organization culture and responsiveness factors ($C6$). Flow of information ($C4$), relationship and decision making ($C5$) are weak areas. In the era of Industry 4.0, no organization can sustain without technology upgradation and smooth flow of information in the supply chain. Therefore, management needs to apply different technologies of Industry 4.0 such as artificial intelligence, cloud computing, Big Data analytics and machine learning for smooth integration of manufacturing systems. Top management needs to support for these initiatives by making investments and skilling the workforce for these emerging technologies. The organization also needs to develop the holistic strategy for operations, marketing, HR and business intelligence for successful coordination in the present Industry 4.0 environment.

Lu (2017) also analyzed similar kind of operational challenges in implementing Industry 4.0 technologies such as IoTs, cyber physical systems (CPS), ICT and enterprise architecture. The study also observed that some countries have taken policy decisions to implement Industry 4.0 in an aggressive manner across all organizations. China has launched China Manufacturing 2025 (CM2025), which is on the track of Industry 4.0. We can compare this index for coordination of the supply chain with other organizations equipped with Industry 4.0 technologies for benchmarking purpose. The comparison will help the organization to compare different coordination groups, based on which weak link in the coordination of the supply chain could be analyzed and improved.

4. Conclusion

In the Industry 4.0 environment, supply chain coordination is essential for sustaining in the globalized market. To improve coordination in the supply chain, its evaluation and comparison with best in the industry are essential. This study has tried to suggest a framework for measuring the coordination index of a supply chain in the current business scenario. Total 32 factors for evaluating coordination in supply chains are identified. These are further grouped into six categories. The graph theoretic approach has been used in this study. For effective benchmarking, it is considered as a powerful tool to evaluate the degree of coordination in the supply chain. Factors and their interdependencies are visually represented by a digraph. The factors' matrix converts the digraph into mathematical form. The coordination index is determined by the mathematical model named factor's permanent function.

It is observed that presently for improving coordination in the supply chain, top management is giving more focus on organizational factors such as lean organization structure, organization culture and responsiveness factors. Flow of information, relationship and decision making are weak areas. Therefore, this organization needs to work on information flow and relationship building in the supply chain. Especially in the era of Industry 4.0, flow of information and upgradation of technological infrastructure are very important. Findings will motivate other organizations to adopt different Industry 4.0 technologies such as IoTs, AI, CPS and ICTs for improving coordination in supply chains.

Although the approach suggested in this study will be highly useful for benchmarking purpose, it has got some limitations. A major limitation is that the value of the coordination index may be influenced by the biased approach of experts in decision making. The proposed coordination framework of the study also needs to be validated on the basis of empirical studies before generalization. This study can be further extended for analyzing other issues of the supply chain such as flexibility, agility, overall performance, etc., and for comparing different sector's performance.

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