Lean supply chain and industry 4.0: a study of the interactions among practices and technologies

Rossini M.*, Kassem B. *, Costa F. *, Portioli-Staudacher A.*

* *Department of management, economics and industrial engineering, Politecnico of Milano, Via raffaele Lambruschini, 4B 20156 – Milano – Italy (matteo.rossini@polimi.it, bassel.kassem@polimi.it, Federica.costa@polimi.it, alberto.portioli@polimi.it)*

Abstract: The ever-increasing competition due to the rapidly changing environment and businesses pushes to complement the adoption of Lean Supply Chain (LSC) with further concepts or tools. Among these, Industry 4.0 (I4.0) presents the same focus on the reduction of costs and wastes and on the increase of efficiency along the whole supply chain as LSC. Therefore, this paper investigates how practices, technologies of LSC and I4.0 interact with each other. The final aim is to provide a comprehensive overview of the interactions in order to acquire a thorough knowledge about the direction of their interrelation, which represents a current gap in the literature. Interpretive Structural Modelling (ISM) techniques are adopted for the analysis of the relationships between LSC and I4.0 practices. The results reveal a mutual beneficial interaction of the two paradigms considered. Indeed, the outcomes obtained show a twofold positive effect between the application of Lean Supply Chain and Industry 4.0. According to this, a series of useful implications are presented, intended not only for academic purpose but also for business application, including limitations and recommendations for further studies.

Keywords: Lean Supply Chain, Industry 4.0, Interpretive Structural Modelling, Interpretative Ranking Process.

1. Introduction

Nowadays, the competition has shifted from firm vs firm to supply chain vs supply chain; thus, it is not enough anymore to be efficient only inside the boundaries of the single company (Frazzon, Tortorella, Dávalos, Holtz, & Coelho, 2017), rather the whole supply chain needs to be efficient in order to be competitive in the market (Thürer M., Zhang H., Stevenson M., Costa F., Ma L., 2020). Hence, the implementation of Lean Supply Chain (LSC) has become a relevant competitive advantage and an effective way to improve performances (Rossini & Portioli, 2018). Beside this, the application of LSC as a stand-alone managerial paradigm has resulted to be confining in the nowadays business scenario (Powell, Romero, Gaiardelli, Cimini, & Cavalieri, 2018). Therefore, the implementation of Lean along the supply chain needs to be complemented with further concepts or tools, and the advent of Industry 4.0 (I4.0) paradigm raised enthusiasm about potential of combining Lean practices and I4.0 technologies (Torri, Kundu, Frecassetti, & Rossini, 2021; Tortorella, Rossini, Costa, & Portioli-Staudacher, Alberto Sawhney, 2019).

Given the novelty of the conjoint application of LSC and I4.0, the paper focuses on the interrelations between these two paradigms in order to understand if LSC can facilitate the implementation of Industry 4.0 increasing the overall business results and vice versa. The two paradigms have been widely studied separately, but there is a lack of knowledge about the relationship between the two (Núñez-Merino, Maqueira-Marín, Moyano-Fuentes, & Martínez-Jurado, 2020). Indeed, only few researches were found in the literature review concerning LSC and I4.0.

Three different schools of thought were identified in the literature. The first group of authors claim that Lean could become a facilitator in the implementation process of Industry 4.0 since Lean work environment nurtures a culture more receptive to new technologies, especially the ones that reduce waste (Powell, 2013; Rossini, Cifone, Kassem, Costa, Portioli-Staudacher, 2021). On the other hand, the second way of thinking argues that digitalizing the supply chain has a significant impact on the implementation of Lean along the supply chain (Sanders, Elangeswaran, & Wulfsberg, 2016). Lastly, many studies have considered I4.0 and Lean as mutually supportive, where Lean methods are seen as facilitators of Industry 4.0 and I4.0 is analysed as a factor strengthening Lean (Ciano, Dallasega, Orzes, & Rossi, 2020). In this sense, Lean and Industry 4.0 are considered complementary since they have the same goal of reducing the costs and increasing the productivity for companies. However, none of them have addressed in a systematic way the study of the interactions between items of the two paradigms. In fact, some studies have focused on the link between specific technologies of I4.0 and concepts of LSC while others investigated the relationship at plant level, without considering the supply chain perspective. Then, still others focused on specific industries or countries. Therefore, the aim of this study is to investigate the relationship between the two paradigms at a more comprehensive level, without focusing on specific technologies or industries. Therefore, the purpose of this research is to investigate interactions of the LSC practices and I4.0 technologies with the final aim of positioning in one of the three schools of thought identified in the literature. The research question that the authors have formulated in this scenario is:

RQ: How do Lean Supply Chain practices and Industry 4.0 practices influence each other?

2. Methodology

Interpretive Structural Modelling (ISM) is "a methodology that formulates a complex system into a visualized hierarchical structure and helps to understand the direct and indirect relationships among the variables affecting the system under consideration" (Sage, 1977). Another definition of ISM found in the literature is "a familiar technique to structure the complex pattern of contextual relationship among a set of variables, affecting the system under consideration, into a comprehensive systematic model using some basic concept of graph theory" (Khaba et al., 2018). In this context where LSC and I4.0 paradigms involve a big number of items with a huge combinations of relationships, ISM is the appropriate methodology to use to face a complex issue where a systematic and logical thinking approach is needed. Indeed, this technique provides order and direction for numerous complex relationships among variables (Sage, 1977). Therefore, it is a computer-assisted learning process that allows researchers to acquire a deeper understanding of the relationship among key issues in different research fields (Soti et al., 2011).

ISM is widely spread in the literature because it allows to consider qualitative factors integrating elements measured on ordinal scales and explaining how the elements are related each other. The final outcome of ISM is the rank of the variables according to their influence on the whole system. The rank is considered as a driving power; therefore, the higher the driving power of the element, the greater the importance of the element (Sage, 1977). The methodology uses systematic application of some elementary notions of graph theory and Boolean algebra in such a way that when implemented in a man machine interactive mode, theoretical, conceptual and computational leverage is exploited to construct a hierarchical graph (Attri et al., 2013).

ISM methodology runs with some assumption (Attri et al., 2013):

1. Modelers should have the sufficient knowledge and experience about the research environment built;
2. In developing Structural Self-Interaction Matrix (SSIM), unique contextual relationship exists between any pair of variables of the system under consideration out of four possible contextual relationships;
3. The contextual relation being modelled is transitive and multilevel;
4. The data are acquired and organized into a reachability matrix in order to facilitate the development of a structural model.

ISM is a structured method that is composed by seven different steps that the researchers should follow. A graphic scheme of the ISM procedure is provided in Figure 1, while each step is described in detail below.

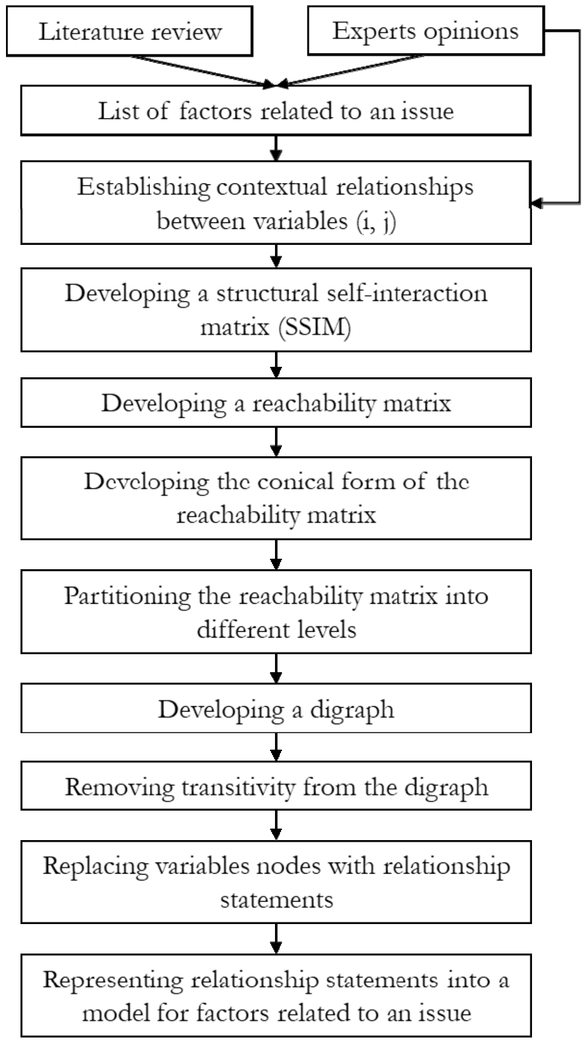

Figure 1: ISM procedure

Step 1: Identification of the Structural Self-Interaction Matrix (SSIM)

In order to apply ISM, there is the need of collecting experts opinions based on various management techniques such as survey and brainstorming in order to develop the contextual relationship among the selected variables. The selected team of experts should focus on the specific research question and should validate the sampled variables providing the relationship between these variables. According to this, the following four symbols are used to denote the direction of the relationship between two factors i and j:

- V if the factor i influence factor j
- A if the factor i is influenced by factor j
- X if factor i and j influence each other
- O if factor i and j are unrelated

Based on the contextual relationship, the SSIM is developed. To obtain consensus, the SSIM should be further discussed with a group of experts. On the basis of their responses, SSIM must be finalized (Attri et al., 2013).

Step 2: Development of initial Reachability Matrix (RM)

The next step in ISM approach is to develop an initial Reachability Matrix starting from the Structural Self-Interaction Matrix. In order to do this, SSIM is converted into the initial RM by substituting the four symbols (V, A, X and O) with a binary number. The conversion into a binary form is performed according to the following rules:

- If the entry (i, j) is V in SSIM, then the corresponding entry in the RM will be 1 in (i, j) and 0 in (j, i);

- If the entry (i, j) is A in SSIM, then the corresponding entry in the RM will be 0 in (i, j) and 1 in (j, i);

- If the entry (i, j) is X in SSIM, then the corresponding entry in the RM will be 1 in both (i, j) and (j, i);

- If the entry (i, j) is O in SSIM, then the corresponding entry in the RM will be 0 in both (i, j) and (j, i).

Step 3: Development of final Reachability Matrix (RM)

This step consists in the incorporation of the transitivity principle in the Initial Reachability matrix in order to develop the final one. Specifically, transitivity is established by checking if variable "A" influences variable "B" which subsequently influences variable "C"; in this case "A" has an influence also over "C" (Soti et al., 2011). In this phase, 1* entries are included to incorporate transitivity to fill the gap, if any, in the opinion collected during the development of Structural Self-Interaction Matrix (Attri et al., 2013).

Step 4: Conical matrix

The conical matrix is developed by clustering variables in the same level across the rows and columns of the final reachability matrix. The driving power of a factor is derived by summing up the number of ones in each row and the dependence power by summing up the number of ones in each column. Afterwards, driving power and dependence power ranks are calculated by giving highest ranks to the factors that have the highest values.

Step 5: Level partitioning

Starting from the final Reachability Matrix, the reachability sets and antecedent sets should be identified for each factor. The reachability set consists of the factor itself and the factors that it impacts. The antecedent set consists of the factor itself and the factors that have an influence over it. Thereafter, the intersection of these sets is derived for all the factors and the levels of the different factors are determined. In the ISM hierarchy, the factors for which the reachability and the intersection sets are the same occupy the top-level. The top-level factors are those factors that will not lead to the other factors above their own level in the hierarchy. Once the top-level factors are identified, they are removed from consideration. Then, the same process is repeated to find out the factors in the next level. This process is continued until the level of each factor is found (Attri et al., 2013).

Step 6: Development of digraph

From the level partitioning, the preliminary digraph including transitive links is obtained. It is generated by nodes and lines of edges. After removing the indirect links, a final digraph is developed. A digraph is used to represent the elements and their interdependencies in terms of nodes and edges, or, in other words, the digraph is the visual representation of the elements and their interdependence. In this development, the top-level factor is positioned at the top of the digraph and second level factor is placed at second position and so on, until the bottom-level factor is placed at the lowest position in the digraph.

Step 7: Development of ISM model

Digraph is converted into an ISM model by replacing nodes of the factors with statements.

3. Variables selection

Given a comprehensive survey of literature about LSC and I4.0, the number of practices listed results to be onerous. Since the authors are conscious of the computational limitations of ISM technique, a structured selection of the most appropriate factors has been performed. Regarding LSC, authors based on the work of Tortorella et al. (2017) and focused on LSC practices belonging to operative clusters of Logistics Management (LOM) and Elimination of Waste and Continuous Improvement (EWCI), namely: Efficient and continuous replenishment, Material handling systems, Standardized work procedures to assure quality achievement, Open-minded and in-depth market research conducted jointly, Inbound vehicle scheduling, Outbound transportation, Establishment of distribution centers, Functional packaging design, Kanban or pull system, Levelled scheduling or heijunka,, Consignment stock, Win-win problem solving methodology, Value chain analysis or value stream mapping. Regarding I4.0 paradigm, nine items has been identifies (Ramirez-Peña et al., 2019): Big data and analytics, Autonomous and collaborative robots, Simulation, Horizontal and vertical integration, Industrial Internet Of Things (IoT), Cybersecurity, Cloud, Additive manufacturing, Augmented reality. Table 1 resumes investigated items of LSC and I4.0 paradigms.

Table 1: ISM items

	Practice
P1 (LSC)	Efficient and continuous replenishment
P2 (LSC)	Material handling systems
P3 (LSC)	Standardized work procedures to assure quality achievement
P4 (LSC)	Open-minded and in-depth market research conducted jointly
P5 (LSC)	Inbound vehicle scheduling
P6 (LSC)	Outbound transportation
P7 (LSC)	Establishment of distribution centers
P8 (LSC)	Functional packaging design
P9 (LSC)	Kanban or pull system
P10 (LSC)	Levelled scheduling or heijunka
P11 (LSC)	Consignment stock
P12 (LSC)	Win-win problem solving methodology
P13 (LSC)	Value chain analysis or value stream mapping
P14 (I4.0)	Big data and analytics
P15 (I4.0)	Autonomous and collaborative robots
P16 (I4.0)	Simulation
P17 (I4.0)	Horizontal and vertical integration
P18 (I4.0)	Industrial Internet Of Things (IoT)
P19 (I4.0)	Cybersecurity
P20 (I4.0)	Cloud
P21 (I4.0)	Additive manufacturing
P22 (I4.0)	Augmented reality

4. Results

In order to ensure the heterogeneity between academic world and manufacturing world, different expert figures have been selected. Indeed, we sent questionnaire to experts belonging to universities, manufacturing companies and consultancy companies. We received 13 responses, 2 from academics, 3 from consultants and 8 from practitioners in manufacturing company (i.e production manager). We adopted ISM methodology strictly following procedure descripted in chapter 2, and preliminary digraph formed by nodes and lines of edges is obtained by the level partitioning. Then, after removing the indirect links, the final digraph is derived and reported in Figure 2.

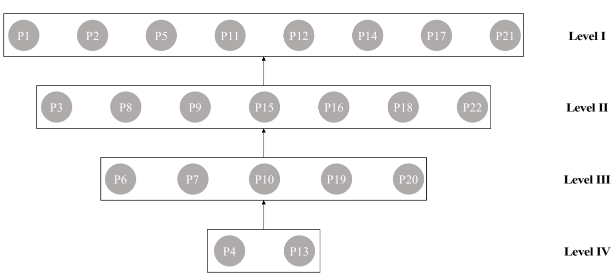

Figure 2: ISM output

Starting from Level IV, it was discovered that Open-minded and in-depth market research conducted jointly (P4) and Value chain analysis or value stream mapping (P13) are the most important practices in the complex network of relationships of the system. Therefore, these practices could have absolute priority in the implementation respect to the others because all the other practices would benefit from their application. Indeed, Value chain analysis or value stream mapping (P13) has high level of driving power and low level of dependence power, being Independent; while Open-minded and in-depth market research conducted jointly (P4) is an Autonomous variable, it cannot be influenced by any other practice but still it can influence directly or indirectly a bunch of them. The willingness to implement open-minded and in-depth market research conducted jointly (P4) leads to have a higher volume of data to handle. This huge amount of information can be more easily stored and shared throughout the organization using the cloud. To properly extract the needed information from the large volume of data, it is necessary to use big data and analytics. In addition, for companies that are conducting jointly open-minded and in-depth market research it will be easier to analyse possible scenarios with the help of simulation. Therefore, the proper implementation of this LSC practice, that is actually not well explored, could support and justify the usage of a bunch of Industry 4.0 technologies. Doing value chain analysis or value stream mapping (P13) allows to create a precise process mapping and so to implement an efficient and continuous replenishment system as well as an appropriate material handling system. In addition, through value chain analysis or value stream mapping it is possible to define the parameters needed to implement the kanban o pull system. Furthermore, it allows to define capacity and location of distribution centers.

Moving on, in the Level III of the ISM model there are Outbound transportation (P6), Establishment of distribution centers (P7), Levelled scheduling or heijunka (P10), Cybersecurity (P19) and Cloud (P20). Outbound transportation (P6) and Levelled scheduling or heijunka (P10) have high driving power and medium dependence power, lying on the boundary between Independent and Linkage. However, they behave as Independent entities and the medium dependence power justifies their positioning in Level III of ISM. Establishment of distribution centers (P7) is characterized by medium driving and dependence power. The positioning in this level is confirmed by the fact that it is influenced by other practices of the same level and also by a practice of the higher level. Cybersecurity (P19) and Cloud (P20) present quite high values of both driving and dependence power. The fact that they influence practices of lower levels but are influenced by P4 is the reason of the positioning in Level III. The development of an outbound transportation (P6) system allows to foster the improvement of the functional packaging design and also supports the implementation of the kanban or pull system. Furthermore, a standardized outbound transportation makes it possible to use the Autonomous and collaborative robots at their best. The implementation of the heijunka (P10) creates a sort of levelling that allows to standardize the work procedures and assure the quality achievement. Moreover, it also favors the planning and management of the transportation both inbound and outbound. Through the establishment of distribution centers (P7), it is possible to optimize the inbound and outbound flow, levelling eventual anomalies through heijunka. The implementation of an appropriate cybersecurity (P19) system and of the cloud (P20) contribute to make more robust, functional and interconnected the implementation of industrial IoT. In addition, the cloud (P20) fosters the diffusion of real-time information that allows to make more effective the application of the augmented reality.

Then, in Level II there are Standardized work procedures to assure quality achievement (P3), Functional packaging design (P8), Kanban or pull system (P9), Autonomous and collaborative robots (P15), Simulation (P16), Industrial IoT (P18) and Augmented reality (P22). Standardized work procedures to assure quality achievement (P3), Functional packaging design (P8), Simulation (P16), Industrial IoT (P18) and Augmented reality (P22); Kanban or pull system (P9) is positioned in the second level because the extent to which it can be influenced is higher than the influencing power. In fact, on the contrary, the Linkage practices that have higher influencing power respect to the other way round, were positioned in the upper level, Level II. Autonomous and collaborative robots (P15) practice can be influenced by most of the variables of the same level and of the superior ones of the ISM. The adoption of standardized work procedures (P3) supports the implementation of an efficient and continuous replenishment system. Nonetheless, if there are strict procedures in place, the streamlining of the scheduling inbound would benefit. The optimization of the packaging design (P8) in a functional and standardized way enables the possibility to build a more efficient material handling system also by leveraging on the usage of autonomous and collaborative robots. The implementation of kanban or pull system (P9) allows to establish win-win strategies with the partners and fosters the optimization of some operating activities connected such as efficient and continuous replenishment and material handling system. Resorting to the usage of autonomous e collaborative robots (P15) enables to optimize the material handling system as well as to make the inbound vehicle scheduling more efficient. The real-time data collected through the augmented reality (P22) are an important input for the Simulation performed with the aim of streamlining the decision-making process. In turn, the usage of simulation (P16) in order to understand times and reactions of the system allows to subsequently adopt additive manufacturing at its best and with lower costs. Industrial IoT (P18) is an important support for the material handling system since it can provide real-time information about the location of specific items. Besides that, industrial IoT delivers real-time data that can be collected and analyzed through big data and analytics. The data collected through the augmented reality (P22) can help the self-learning process of the autonomous and collaborative robots.

In the lowest level of the ISM model, Level I, there are the practices that can be influenced through the others at higher levels, in particular Efficient and continuous replenishment (P1), Material handling systems (P2), Inbound vehicle scheduling (P5), Consignment stock (P11), Win-win problem solving methodology (P12), Big data and analytics (P14), Horizontal and vertical integration (P17) and Additive manufacturing (P21).

The results of the ISM highlight that the practices that are able to produce a positive effect on the implementation of all the others are both belonging to the LSC paradigm, Open-minded and in-depth market research conducted jointly (P4) and Value chain analysis or value stream mapping (P13). Despite belonging to different LSC bundles, these practices are oriented towards the same direction, they provide a general methodology for designing the supply chain and organizing the operational activities, thus influencing all the other practices. Some further considerations should be done on Open-minded and in-depth market research conducted jointly (P4). Indeed, it was already reported the fact that it is not an aspect of the LSC deeply explored but, given its high importance in driving the improvement in I4.0 paradigm, the findings are suggesting to concentrate more on the development of this aspect. Considering Value chain analysis or value stream mapping (P13), despite the top-priority positioning occupied in the analysis, the direct and indirect relationships that it undertakes with the I4.0 practices are almost null while it is strictly connected with the practices belonging to the same paradigm.

Then, moving to the lower levels it has been observed that some Industry 4.0 technologies are crucial to support and optimize operative LSC activities, especially related to the LOM bundle. In particular, the I4.0 practice that resulted to be the most connected with the LSC paradigm in both senses is Autonomous and collaborative robots (P15).

5. Conclusions

Given the novelty of the advent of I4.0, the introduction of new technologies in already settled managerial systems is still an open debate. Therefore, the aim of the research has been to investigate interaction and relationship of LSC practices and I4.0 technologies in order to add a piece of knowledge in the literature that explains integration of the two paradigms.

The results of the research confirmed that items of both paradigms interact significantly. However, in order to foster the positive correlation that exist between the Lean Supply Chain and the Industry 4.0 it is necessary to address the implementation of some specific practices. In particular, the most important practices according to the two techniques applied resulted to be Open-minded and in-depth market research conducted jointly (P4) and Value chain analysis or value stream mapping (P13) for what concerns the LSC and Autonomous and collaborative robots (P15), Cybersecurity (P19) and Cloud (P20) regarding the I4.0. It is worth to highlight that while the benefits that the implementation of P4 and P15 can provide on the other paradigm are evident, the prominent importance of P13, P19 and P20 is mainly due to the synergies that they produce on the same paradigm, LSC and I4.0 respectively.

The results obtained contribute to enhance the knowledge in this field, mainly confirming the positive correlation of two paradigms and using an alternative methodology to analyse the research gap. However, this work is a preliminary research and has several limitations. The items selected are a part of the possible items that are present in the literature, both for LSC filed and for I4.0. Moreover, ISM methodology is useful for giving a hierarchical point of view, but it misses causal-relationship indication and moreover it lacks in power of generalization of results.

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