A systematic modelling of Industry 4.0 technologies: an ISM-based approach

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Abstract

To develop supply chain resilience, industries need to adapt the industry 4.0 era technologies efficiently to predict and sustain the global supply chain. From the extensive literature review, most of the research in the industry 4.0 era talks about the applicability of individual technologies. Still, it lacks to explain the application of the industry 4.0 technology collaboratively. Based on the extensive literature review, we found that there exists a dilemma among the industries as to when which technology to be adopted and how can it be collaborated with the existing infrastructure of industry 3.0 era to drive growth in the competitive manufacturing environment and also not to burden the capital expenditure. The paper will address the managerial dilemma of adaptation of relevant Industry 4.0 technologies and at which stage. Thirty-five industry 4.0 technologies were selected based on extensive literature review and applicability in the manufacturing industry. ISM (Interpretive structural modelling) method is adopted to help us identify variables associated and systematically develop the contextual relationship between I4.0 technologies. The findings reveal the hierarchical levels of technology (longitudinal and latitudinal) such as base technologies and interaction between them and guide managers to mitigate the risk by systematically adopting industry 4.0 technologies by knowing the interaction between technologies and thus developing supply chain resilience.

Keywords
Supply chain, Supply chain resilience, ISM, Industry 4.0, Industry 3.0

1. Introduction
Industrial revolution from eighteenth century till today is catering to the manufacturing process with focus on supply and demand volatility within value chain(Yin et al., 2018). The third industrial revolution introduced computers, information technology and took a high leap in advancement of electronics sector like use of sensors, actuator, plc and also greater automation in production (Sheth Jenis, 2018) .The Industry 3.0 era paved the way for technology as an instrument for rapid growth and served as a platform for industry 4.0 era.

The mammoth size of supply chains in the globalized world, often led to disruption caused by variables that are not in direct control of the organization. To obtain supply chain resilience, industries need to efficiently adapt the industry 4.0 era technologies to predict and sustain the supply chain across the globe(Macaulay, 2015). The industry 4.0 era however in the context of Indian manufacturing industries is lagging in the application of new technologies like Artificial Intelligence, Virtual Reality, Augmented Reality, Big Data, Block cha (Oztemel & Gursev, 2020) in more so in supply chain context there are many level which are very complex and dynamic, each level makes a mesh and grid network making it difficult to apply industry 4.0 technologies in a systematic manner based on the performance requirement of value chain (Wu et al., 2007). The powerful technologies of industry 4.0 and are still in the doldrums as we talk about the applicability and tangibility in reaction to the rapid change in the global response to supply chain(Schlaepfer RC et al., 2014). Industry in the Indian scenario lacks the basic understanding of their application in the areas where these technologies can spur growth. Some previous researches have proposed models for the adaptation on the other hand there are research related to impact of these technologies in industrial performance. However, there is an urgent need to address the issue of adaptation of industry 4.0 technologies in systematic manner based on the performance need of the organization and how these technologies can be collaborated with the existing infrastructure of industry 3.0 era, to spur growth in the competitive manufacturing environment.

In this study, an ISM based model has been developed to hierarchically distinguish technologies on the basis of company's performance need in supply chain of the company. ISM (Interpretive structural modelling) will help us to identify variables associated, and also to systematically develop contextual relationship between various variable in our case interrelationship between I4.0 variables(Govindan et al., 2015). A few researchers have work in developing the interrelation to identify the Variables in adaptation of Industry 4.0 technologies but there is lack of research in the domain of application of industry 4.0 technology in context of collaboration with industry 3.0 technologies to use technology in decisive manner to achieve growth, sustainability and respond to supply chain disruption. ISM in research has been identified as a tool to form a contextual relationship among variables. It makes unclear model clearer to understand(Luthra et al., 2014). On the basis of extensive literature survey and expert opinion 35 industry 4.0 technologies have been identified.

1.1 Objectives

This research aims to provide following contributions:

- To identify the interrelation among various Industry 4.0 technologies
- To generate a model to identify the application of each technology in hierarchical manner.

2. Literature review

The industry 4.0 term as a concept was coined by Germany and used across Europe to increase the productivity of industrial systems. Industries are in the throes to transform digitally, with this concept from some time they have adopted information technology. But with the advent of stiff competition and development in electronic industry developments are not restricted towards automation, blurring the lines between real and virtual world giving rise to cyber physical systems(Schlaepfer RC et al., 2014).

In the industry value chain in terms of evolution Industry 4.0 represent a new stage of development. Industry 4.0 consist of major technologies: Artificial Intelligence, Bigdata, Augmented reality, Virtual reality, Cloud computing, Internet of things, System integration, Simulation, Additive manufacturing, Autonomous robots. (Fatorachian & Kazemi, 2021; Oztemel & Gursev, 2020; Schlaepfer RC et al., 2014) I4.0 is a set of technologies and concepts that enable real-time communication and interconnection between people, equipment, and products. The I4.0 is the umbrella term for new edge technologies revolutionizing the manufacturing products and processes across the supply chainthrough use of digital technologies (Macaulay, 2015). Industry 4.0 consist of technologies like Artificial Intelligence (Klumpp, 2018), Big Data (Cheng et al., 2016), AR, VR (Nason & Wiklund, 2018), Cloud Computing (Xie et al., 2013), Cyber physical system (Sanchez et al., 2020), IOT (Ben-Daya et al., 2019) which are transforming how conventional processes had been done. I4.0 technologies are making industries to turn around their strategies by shorten production runs, monitoring, shorten lead-times, traceability, efficient use of resources(Pagliosa et al., 2021). Literature review of various research paper served the path to tabulate our research to identify interrelation between 35 technologies

"Artificial Intelligence"- It is a system's ability to acquire insights by analysing data from the external environment and using those learnings to adapt or create new plans in response to the environment. (Grover et al., 2020).AI, Big data both go hand in hand, they are transforming organization by providing them necessary tool to make a quick decision based on the volumes of information available(Grover et al., 2020).Bigdata contains voluminous data artificial intelligence helps to successfully interpret and make it interpretive through use of cognitive computing.(Duan et al., n.d.). AI capability would analyse the system responsiveness to supply chain disruptiveness for e.g., if some part is not available in one value chain of products, AI systems can analyse other value chain and existing stored volumes can be utilize to remove the disruptiveness caused due to material shortages in the value chain hindering efficient production.(Klumpp, 2018)

"Big data" - is done on the data obtained from CPS to further do continuous improvement and reduce defects.(Cheng et al., 2016). (Schlaepfer RC et al., 2014) suggests leveraging of data sources will foster connection of data and will give insights which are actionable in nature for decisive competitive advantage

"Augmented reality and Virtual reality"- Augmented Reality (AR) has been defined as a system which supplements the real world with virtual (computer- generated) objects that appear to coexist in the same space as the real world" (Azuma et al., 2001). As a knowledge-sharing tool, AR will assist firms in transitioning from a resource-based perspective to more versatile resources that promote agility and growth(Nason & Wiklund, 2018) .AR can help in saving the information for future use as with the passing of time there is slippage or migration of process (van Lopik et al., 2020). AR/VR helps in better utilization of resource time saving and helps to improve performance of supply chain indicators (Jetter et al., 2018). Additive manufacturing technologies can be leveraged by using with other technologies like AR/VR to(Kubáč & Kodym, 2017). AR VR and MR enhance interaction parameters of immersive, interactivity and multi-perception. Key components of AR are sensors and cameras, projection screen, reflection (mirror). Sensor based AR environment provides multimodal and multisensory medium for operators in manufacturing industry to learn from performance data and expert experience.(Limbu et al., 2018). The Use of AR in facility planning by visualizing and simulating the ware house before even beginning the construction will help the organization in capacity planning efforts to make supply chain robust and flexible (Merlino & Sproge, 2017).In the advent of Industry 4.0 revolution disruptive technologies like IOT, VR, Big data are vulnerable to cyber security owing to rapid changing global supply chain and affects the multiple stake holders of businesses(Ghadge et al., 2020)

“Cloud computing”- It consist of physical infrastructure like servers and is connected to basic I3.0 infrastructure of internet. Its operation depends upon power, optical fibre and both physical and cyber components.(Rao et al., 2012). With the development of CC, cloud-based RFID system are finding more usability in industries (Xie et al., 2013). Internet and information collection device like QR code Bar code give cloud-based system real time information to capture the current status of production in production line(Qu et al., 2014). In the paper (Laubhan et al., 2016) a sensor network is formed which is wireless with transducers. The transducer collects the data and with integration with cloud-based system give accessibility to the user. In the paper cloud-based servers are connected with Bluetooth technology to serve a relationship between cloud based and Bluetooth technology.(Fraga-Lamas et al., 2020). Jazdi (2014) affirms that a CPS connected to the cloud is often referred as ‘IOT”. Some supply chain problems can be address by mobile technologies which are again connected with cloud-based server for real time information integration.(Sanchez et al., 2020). Srinivasan and Dey (2014) has proposed framework electronic supply chain by integrating ERP software with supply chain system and electronic supply chain is enabled by mobile based technologies.(Barata et al., 2018). The SCADA system technology is leveraged with combination of IOT which can give real time status report pertaining of error via cloud-based servers.

“Internet of Things”- It provides a network of digital objects interconnected with physical components like sensors and other devices within industry or outside the industry with stakeholders to provide visibility to supply chain. (Ben-Daya et al., 2019). IOT provides base platform for various Cyber Physical System which uses sensor network, actuators and transducers. IOT systems has introduced a new concept Cloud manufacturing by using cloud-based technologies. Data from smart objects which are connected to technologies of I4.0 this data collected will give incredible insights and will improve the overall traceability and visibility of supply chain. IOT technology is leveraged by interconnection of sensor and actuating device this will create an unified framework for innovative technology this is achieved by sensing and cloud computing. (Gubbi et al., n.d.)

“Cyber security”- When machines are connected through cyber space via the internet where IOT systems are used to increase its operational efficiency the physical systems are vulnerable to cyber- attacks, system vulnerabilities and this can be overcome by using cyber security architecture framework like EC 62443(Lezzi et al., 2018). Although, there is a security challenge in industrial environments due to the presence of connected CPSs, that is, mostly these systems were not designed by keeping the goal of cybersecurity in the minds because, the security was ensured by the isolation of the manufacturing systems and also physical access control. Whereas, the modern machines have been provided with many smart devices (such as actuators and sensors) and are connected to other data processing systems or machines via either wired Ethernet or wireless networks.

“Block chain”-(Fernández-Caramés et al., 2019) in its paper increased the robustness of UAV system (Autonomous vehicle) use for collecting data and enhancing traceability of industry items attached with RFID tags by using blockchain, validate them, ensure their trustworthiness and make them available to the interested parties. The block technology can be applied in internet of things related applications (Ferrag, M.A et. al 2019). Block chain is driving current prevalent infrastructure to decentralized environment providing security, trust and auditability.(Hassan et al., 2019). Block chain can help to effectively prevent attack on network infrastructure by decentralizing services (Kaid et al., n.d.)

“Simulation”-AI guided virtual reality system can overcome the limitation of human mind to dessimate knowledge and rapidly transform into applicable business solution .AI can offer to simulate multiple virtual work flows to simulate best optimized solution.(van Lopik et al., 2020). AI guided virtual reality system can overcome the limitation of human mind to dessimate knowledge and rapidly transform into applicable business solution .AI can offer to simulate multiple virtual work flows to simulate best optimized solution.(van Lopik et al., 2020)

"Cyber physical system"- IOT is the subset of CPS where IOT is use to make physical system connected to internet through sensors and actuators. CPS system is becoming more dynamic, decision regarding advanced CPS along with AI will not be understandable to common worker for production processes.(Klumpp, 2018). In CPS interaction between physical state of device make it more dynamic in which it is interlinked with cyber world and physical space by sensing, computation and control.(Wollschlaeger et al., 2017a). CPS connects physical and cyber systems by integrating the analogue and digital components and CM which has been identified by higher scalability and agility. (Cheng et al., 2016). Maintenance services technician can work more efficient by using mobile application working with CPS (Wittenberg, 2016). Machine in today's world can be more connected with I4.0 technologies to gather data for actionable execution like with manufacturing enterprise system and Enterprise resource planning software's. (Wittenberg, 2016). Human machine interface has been evolved with the introduction of cyber physical systems as to develop a standard module which can run from any device.(Tsochev & Sharabov, 2021a).

3 Problem description

In the advent of global supply chain and supply chain disruption often manufacturing companies faces dilemma on how to introduce new technologies to predict and prevent future disruption. They are in sense of confusion as to develop an overall new infrastructure for industry 4.0 technologies or to use existing industry 3.0 infrastructure as a base. Manufacturing industry often faces difficulty in collaborating different technologies as they have been adapted in tandem.

4 Methodology

ISM (Interpretive Structural Modelling) is a method to effective form variables and to identify contextual relationship among the variables in our case I4.0 variables (Luthra et al., 2014). Here are the steps to build ISM

- Variable constituting the system have been identified by extensive literature review
- Contextual relationship between industry 4.0 technologies that are variables in this case are identified by citing the literature associated with it.
- SSIM Structural self-interaction matrix are established that indicated the pairwise relationship among industry 4.0 variables
- The next step is to develop reachability matrix from "SSIM"
- Transitivity linkages as shown in Figure 1 are to be checked

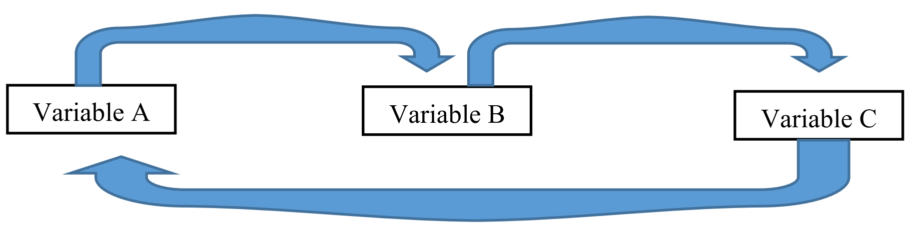

Figure 1. Transitivity linkages

4.1 Data collection

Variables has been identified based on extensive literature review and expert opinion. Search engine used was google scholar and Scopus database with keywords identified using snowball approach. And it is pairwise used to cite the interrelation between various variable. I4.0 technologies identified are tabulated in Table 1

Table 1. Selected technologies for Industry 4.0 adaptation framework

C1. Sensors	C8. 4G/5G	C15. ERP	C22. COBOTS	C29. AI
C2. Actuators	C9. WIFI	C16. Embedded software	C23. Industry wearable system	C30. Big data analytics

C3. PLC	C10. Network infrastructure	C17. SCADA	C24. Digital machine	C31. Autonomous robots
C4. Transducers	C11. Bluetooth	C18. Internet of things	C25. Advanced material	C32. Virtual reality
C5. Barcode	C12. System integration	C19. Cloud	C26. Machine learning	C33. Augmented reality
C6. RFID	C13. Mobile technologies	C20. Additive mfg.	C27. Cyber physical system	C34. Simulation
C7. Internet	C14. MES	C21. Mechatronics	C28. Cyber security	C35. Block chain

4.2 Structural self-interaction matrix development

The ISM methodology was designed for group learning, but can also be applied individually(Kannan & Haq, 2007). ISM helps in transforming complex threads of relationship into model with clearer relationship. (Sushil, 2012) explains the use of ISM in complex issues requiring analytical and logical thinking. (Kannan & Haq, 2007) propose the ISM methodology for analysing the interactions of criteria and sub criteria for the selection of suppliers for a build-to-order company. (Diabat et al., 2013) implemented an ISM model in third party logistics to develop the factors affecting the implementation of green supply chain management. Table shows contextual relationship in matrix between any two variables i and j and their direction has been examined

Symbols used are "V", "A", "X", "O" have been utilized to signify the direction of variables

V-Technology variable i leads to technology variable j ;

A-Technology variable j leads to technology variable i ;

X-Technology variable i and j leads to each other;

O- Technology variable i and j are not related to each other;

Table 2 shows SSIM matrix, in the matrix notation it indicates technology C1(sensor) and C2(actuators) are not related to each other a symbol "O" is denoted at the intersection of C1 and C2. C1(sensor) and C7(internet) serves as the building block for C18(IOT) and helps to achieve C18 but vice versa is not valid. Hence, symbol "V" is denoted at the intersection of C1, C18 and C7,C18. C12(System integration) and C13(mobile technologies) helps each other to achieve therefor symbol "X" is denoted in the intersection of C12 and C13. C9(WIFI) is used to provide infrastructure to C7(internet) in the manufacturing industry context not vice versa hence, a symbol "A" is denoted in the intersection of C7 and C9.

4.3 Initial reachability matrix

The SSIM is converted into a matrix consisting of binary number 0 and 1 based on the substitution rule given below

- If X_{ij} value in the SSIM is "V", X_{ij} value will be 1 and X_{ji} value will be 0
- If X_{ij} value in the SSIM is "A", X_{ij} value will be 0 and X_{ji} value will be 1
- If X_{ij} value in the SSIM is "X", both X_{ij} value and X_{ji} value will be 1
- If X_{ij} value in the SSIM is "O", both X_{ij} value and X_{ji} value will be 0

Table 3 shows initial reachability matrix which is converted into binary number based on the above rules.

Table 2. SSIM for I4.0 technologies

	C35	C34	C33	C32	C31	C30	C29	C28	C27	C26	C25	C24	C23	C22	C21	C20	C19	C18	C17	C16	C15	C14	C13	C12	C!!	C10	C9	C8	C7	C6	C5	C$	C3	C2	C1
C1	A	V	V	V	V	V	A	O	V	O	A	V	V	V	V	V	V	V	V	A	O	O	V	A	X	V	A	V	O	X	O	O	O	O	X
C2	A	O	V	V	V	V	A	O	V	O	A	V	O	O	V	O	V	V	V	A	O	O	V	A	A	V	O	V	O	O	O	O	O	X	
C3	O	V	O	V	O	V	O	O	V	O	O	V	O	V	V	O	A	V	O	A	O	O	A	V	O	V	O	V	O	O	O	O	X		
C4	O	O	V	O	V	O	O	O	V	O	O	V	O	V	V	O	V	V	V	O	O	O	V	A	O	O	O	O	O	O	O	X			
C5	V	O	O	O	O	O	O	O	V	O	O	O	A	O	O	O	A	V	O	O	O	O	A	A	O	O	O	O	O	O	X				
C6	V	O	O	O	O	O	O	O	V	A	O	V	A	X	V	O	A	V	O	O	V	V	A	X	O	O	X	O	O	X					
C7	V	O	O	V	O	O	V	A	V	O	O	O	V	O	O	V	V	V	O	O	O	O	V	V	A	A	A	V	X						
C8	O	O	O	V	O	O	V	O	V	O	A	O	V	V	O	O	V	V	V	A	O	O	V	X	O	A	O	X							
C9	V	O	O	V	V	O	O	O	V	O	O	O	V	O	O	V	V	V	V	X	O	O	V	V	O	A	X								
C10	V	O	V	V	O	V	O	O	V	O	A	V	V	O	V	V	V	V	O	V	V	V	O	V	A	X									
C11	O	O	V	V	O	O	V	O	V	O	O	O	V	O	O	O	X	V	V	A	O	O	V	V	X										
C12	V	A	A	A	X	V	V	O	A	O	O	V	A	V	V	X	A	A	X	A	X	X	X	X											
C13	A	O	V	V	O	V	V	O	V	A	O	V	V	O	O	V	A	X	V	O	V	V	X												
C14	O	O	O	O	O	O	O	O	A	O	O	V	A	A	A	O	A	A	A	X	O	X													
C15	X	V	O	O	O	A	A	O	O	A	O	O	A	O	O	O	A	A	O	O	X														

C16	X	V	V	V	V	O	A	O	V	A	O	V	V	V	V	O	A	V	O	X															
C17	A	A	A	O	O	A	A	O	V	A	O	O	O	O	A	O	A	V	X																
C18	A	A	V	V	V	V	A	A	V	A	O	V	V	V	O	O	A	X																	
C19	O	O	V	V	V	V	A	A	V	V	O	V	V	V	V	V	X																		
C20	O	O	O	O	O	O	A	A	O	O	V	O	O	O	V	X																			
C21	O	O	A	O	V	O	O	O	V	O	A	V	O	V	X																				
C22	O	O	A	O	O	A	A	O	V	A	A	O	O	X																					
C23	O	V	A	A	V	A	A	O	V	V	A	V	X																						
C24	O	A	O	O	O	A	A	O	V	O	O	X																							
C25	O	O	O	O	O	O	O	O	O	O	X																								
C26	X	V	X	X	V	V	X	V	V	X																									
C27	O	A	A	A	V	O	A	A	X																										
C28	A	O	O	V	O	O	A	X																											
C29	A	V	V	V	V	A	X																												
C30	O	A	A	A	O	X																													
C31	O	A	A	O	X																														
C32	O	V	O	X																															
C33	O	V	X																																
C34	O	X																																	
C35	X																																		

Table 3. Initial reachability matrix

	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	c16	c17	c18	c19	c20	c21	c22	c23	c24	c25	c26	c27	c28	c29	c30	c31	c32	c33	c34	c35
C1	1	0	0	0	0	1	0	1	0	1	1	0	1	0	0	0	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1	1	0
C2	0	1	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	1	1	0	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0
C3	0	0	1	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	1	1	0	1	0	0	1	0	0	1	0	1	0	1	0
C4	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	1	1	0	1	0	0	1	0	0	0	1	0	1	0	0
C5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
C6	1	0	0	0	0	1	0	0	1	0	0	1	0	1	1	0	0	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	1
C7	0	0	0	0	0	0	1	1	0	0	0	1	1	0	0	0	0	1	1	1	0	0	1	0	0	0	1	0	1	0	0	1	0	0	1
C8	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	1	1	0	0	1	1	0	0	0	1	0	1	0	0	1	0	0	0
C9	1	0	0	0	0	1	1	0	1	0	0	1	1	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
C10	0	0	0	0	0	0	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	0	1	1	0	0	1	0	0	1	0	1	1	0	1
C11	1	1	0	0	0	0	1	0	0	1	1	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	1	0	0	1	1	0	0
C12	1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	1	1	1	0	0	0	1
C13	0	0	1	0	1	1	0	0	0	0	0	1	1	1	1	0	1	1	0	1	0	0	1	1	0	0	1	0	1	1	0	1	1	0	0
C14	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
C15	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
C16	1	1	1	0	0	0	0	1	1	0	1	1	0	1	1	1	0	1	0	0	1	1	1	1	0	0	1	0	0	0	1	1	1	1	1
C17	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
C18	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0	1	1	1	0	0	1	0	0	1	1	1	1	0	0
C19	0	0	1	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	0	0
C20	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
C21	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	1	0	0	0	0
C22	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
C23	0	0	0	0	1	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	1	0	0	1	0
C24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
C25	1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
C26	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1
C27	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
C28	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0
C29	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0
C30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	1	0	0	0	0	1	1	0	0	0	0	0
C31	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
C32	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	1	0	1	0	1	0
C33	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	1	1	1	0	0	1	1	0	0	1	1	0	1	1	0
C34	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	1	0
C35	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	1

4.4 Final reachability matrix

The final reachability matrix is obtained after applying transitivity rule as discussed in Figure 1 by changing binary 0 to binary 1. The cells have been highlighted after applying transitivity linkages in Table 4

Table 4. Final reachability matrix

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31	C32	C33	C34	C35
1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1
0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0
1	1	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	0	1
1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1
1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1
1	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	0	1	0	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	1	0	1	0	0	1	0	0	0	1	0	0	1	1
1	0	0	0	0	1	0	0	1	0	0	1	0	1	1	1	0	1	0	0	1	1	0	1	0	0	1	0	0	0	1	0	0	1	1
1	1	0	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0
1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	1	1	0	0	1	1	1	0	1	0	0	1	0	1	1	1	0	0	1	1
0	0	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	0	1	1	0	1	0	0	0	1	0	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	0	1	0	0	1	1	1	0	1	1	0	0	0	1	1	1	1	1	0	1
1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	0	1	0	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1
1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1

4.5 Level partitions

Antecedent and Reachability set for every variable has been identified and an intersection set is developed based on the intersection of variable. For which the interaction is identical has been given level 1 and iteration is continued until each level of variable has been assigned (Kannan & Haq, 2007) (table 5).

Table 5. Levels partitions of technologies

Levels	Industry 4.0 variables
1	C12(System Integration), C14(MES), C15(ERP), C24(Digital Machines), C31(Autonomous robots)
2	C27(CPS)
3	C18(IOT), C22(COBOTS)
4	C17(SCADA)
5	C5(Barcode), C21(Mechatronics), C34(Simulation)
6	C20(Additive manufacturing), C23(IWS), C26(ML), C29(AI), C30(BDA), C32(VR), C33(AR)
7	C3(PLC), C6(RFID), C8(4G/5G), C13(Mobile technologies)
8	C2(Actuators), C7(Internet), C11(Bluetooth), C16(Embedded software), C19(Cloud), C35(Block chain)
9	C1(Sensors), C4(Transducer), C9(WIFI), C10(Network infrastructure), C28(Cyber security)
10	C25(Advance materials)

4.8 ISM model

ISM model is developed from the levels obtained in level partitioning as shown in Figure 2**.** Technologies such as autonomous robots, digital machines are coming in the top level of ISM models these technologies are called front end technologies because this technology serve as end application purpose supported by base level technologies such as sensors, programmable logical unit, actuator etc. that form the platform for advance technologies.

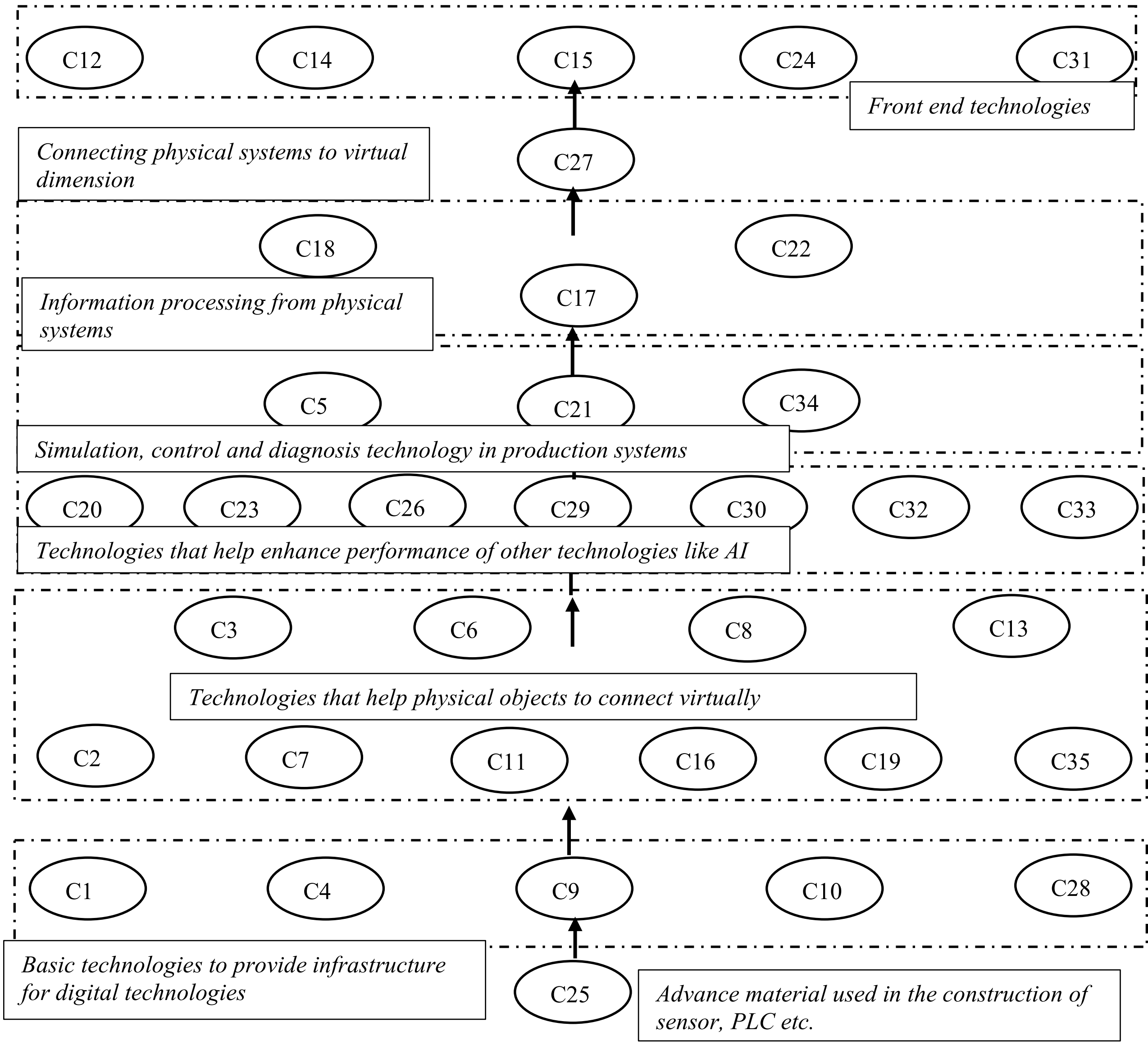

Figure 2. ISM model for Industry 4.0 technologies

5 Conclusion

Industries across the globe are focussing on adapting industry 4.0 technologies. However, there exist the dilemma to adapt the entire ecosystem of technologies or to focus on some technologies based on the value chain requirement of the industry. Based on the extensive literature review and expert opinion, 35 technologies are identified to develop the framework for adaptation with the help of ISM.

In Figure 2. ISM model for Industry 4.0 technologies framework thus obtained comprises of base-level technologies in level 10 which provides infrastructure for digitization. As we move up in the ISM model industries now has the infrastructure for I4.0 technologies and hence making physical object to connect with the virtual environment. The next level is advanced technologies that complement existing processes and technology to enhance efficiency. Now that middle-level technologies have been adapted in the entire supply chain, moving to the next level will guide industries to make robust simulation, control and diagnosis in production systems. Finally, the front end technologies

pave the way for end application for the value chain of the company interacting with each component of the value chain thus improving the supply chain performance and resilience towards undue disruption in supply chain.
The interrelation between technologies has been formulated by literature review and expert opinion however, this model can be further evaluated by structural equation modelling to generalize the model for entire manufacturing industries which can be part of future research direction.

References

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. IEEE Computer Graphics and Applications, 21(6). https://doi.org/10.1109/38.963459

Barata, J., Rupino Da Cunha, P., & Stal, J. (2018). Mobile supply chain management in the Industry 4.0 era: An annotated bibliography and guide for future research. In Journal of Enterprise Information Management (Vol. 31, Issue 1, pp. 173–192). Emerald Group Publishing Ltd. https://doi.org/10.1108/JEIM-09-2016-0156

Ben-Daya, M., Hassini, E., & Bahroun, Z. (2019). Internet of things and supply chain management: a literature review. In International Journal of Production Research (Vol. 57, Issues 15–16, pp. 4719–4742). Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2017.1402140

Cheng, F. T., Tieng, H., Yang, H. C., Hung, M. H., Lin, Y. C., Wei, C. F., & Shieh, Z. Y. (2016). Industry 4.1 for Wheel Machining Automation. IEEE Robotics and Automation Letters, 1(1), 332–339. https://doi.org/10.1109/LRA.2016.2517208

Diabat, A., Khreishah, A., Kannan, G., Panikar, V., & Gunasekaran, A. (2013). Benchmarking the interactions among barriers in third-party logistics implementation: An ISM approach. Benchmarking, 20(6), 805–824. https://doi.org/10.1108/BIJ-04-2013-0039

Duan, Y., Edwards, J. S., & Dwivedi, Y. K. (n.d.). Artificial intelligence for decision making in the era of Big Data-evolution, challenges and research agenda. https://www.youtube.com/watch?v=mNEQsl1-iZs

Fatorachian, H., & Kazemi, H. (2021). Impact of Industry 4.0 on supply chain performance. Production Planning and Control, 32(1), 63–81. https://doi.org/10.1080/09537287.2020.1712487

Fernández-Caramés, T. M., Blanco-Novoa, O., Froiz-Míguez, I., & Fraga-Lamas, P. (2019). Towards an Autonomous Industry 4.0 Warehouse: A UAV and Blockchain-Based System for Inventory and Traceability Applications in Big Data-Driven Supply Chain Management. Sensors (Basel, Switzerland), 19(10). https://doi.org/10.3390/s19102394

Fraga-Lamas, P., Lopez-Iturri, P., Celaya-Echarri, M., Blanco-Novoa, O., Azpilicueta, L., Varela-Barbeito, J., Falcone, F., & Fernández-Caramés, T. M. (2020). Design and Empirical Validation of a Bluetooth 5 Fog Computing Based Industrial CPS Architecture for Intelligent Industry 4.0 Shipyard Workshops. IEEE Access, 8, 45496–45511. https://doi.org/10.1109/ACCESS.2020.2978291

Ghadge, A., Weiß, M., Caldwell, N. D., & Wilding, R. (2020). Managing cyber risk in supply chains: a review and research agenda. In Supply Chain Management (Vol. 25, Issue 2, pp. 223–240). Emerald Group Holdings Ltd. https://doi.org/10.1108/SCM-10-2018-0357

Govindan, K., Azevedo, S. G., Carvalho, H., & Cruz-Machado, V. (2015). Lean, green and resilient practices influence on supply chain performance: interpretive structural modeling approach. International Journal of Environmental Science and Technology, 12(1), 15–34. https://doi.org/10.1007/s13762-013-0409-7

Grover, P., Kar, A. K., & Dwivedi, Y. K. (2020). Understanding artificial intelligence adoption in operations management: insights from the review of academic literature and social media discussions. Annals of Operations Research. https://doi.org/10.1007/s10479-020-03683-9

Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (n.d.). Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions. www.buyya.com.

Hassan, F. ul, Ali, A., Rahouti, M., Latif, S., Kanhere, S., Singh, J., AlaAl-Fuqaha, Janjua, U., Mian, A. N., Qadir, J., & Crowcroft, J. (2019). Blockchain And The Future of the Internet: A Comprehensive Review. http://arxiv.org/abs/1904.00733

Kaid, D., Eljazzar, M. M., & Member, I. (n.d.). Applying Blockchain to Automate Installments Payment between Supply Chain Parties.

Kannan, G., & Haq, A. N. (2007). Analysis of interactions of criteria and sub-criteria for the selection of supplier in the built-in-order supply chain environment. International Journal of Production Research, 45(17), 3831–3852. https://doi.org/10.1080/00207540600676676

Klumpp, M. (2018). Innovation potentials and pathways merging Ai, CPS, and IoT. Applied System Innovation, 1(1), 1–18. https://doi.org/10.3390/asi1010005

Kubáč, L., & Kodym, O. (2017). The impact of 3D printing technology on supply chain. MATEC Web of Conferences, 134. https://doi.org/10.1051/matecconf/201713400027

Laubhan, K., Talaat, K., Riehl, S., Aman, M. S., Abdelgawad, A., & Yelamarthi, K. (2016). A low-power IoT framework: From sensors to the cloud. 2016 IEEE International Conference on Electro Information Technology (EIT), 648–652. https://doi.org/10.1109/EIT.2016.7535315

Lezzi, M., Lazoi, M., & Corallo, A. (2018). Cybersecurity for Industry 4.0 in the current literature: A reference framework. In Computers in Industry (Vol. 103, pp. 97–110). Elsevier B.V. https://doi.org/10.1016/j.compind.2018.09.004

Limbu, B. H., Jarodzka, H., Klemke, R., & Specht, M. (2018). Using sensors and augmented reality to train apprentices using recorded expert performance: A systematic literature review. In Educational Research Review (Vol. 25, pp. 1–22). Elsevier Ltd. https://doi.org/10.1016/j.edurev.2018.07.001

Luthra, S., Kumar, S., Kharb, R., Ansari, M. F., & Shimmi, S. L. (2014). Adoption of smart grid technologies: An analysis of interactions among barriers. In Renewable and Sustainable Energy Reviews (Vol. 33, pp. 554–565). Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.02.030

Macaulay, J. , L. B. and G. Chung. (2015). "Internet of things in logistics."A collaborative report by DHL and Cisco. DHL Trend Research and Cisco Consulting Services, DHL Customer Solutions & Innovation.

Merlino, M., & Sproge, I. (2017). The Augmented Supply Chain. Procedia Engineering, 178, 308–318. https://doi.org/10.1016/j.proeng.2017.01.053

Nason, R. S., & Wiklund, J. (2018). An Assessment of Resource-Based Theorizing on Firm Growth and Suggestions for the Future. Journal of Management, 44(1), 32–60. https://doi.org/10.1177/0149206315610635

Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. In Journal of Intelligent Manufacturing (Vol. 31, Issue 1, pp. 127–182). Springer. https://doi.org/10.1007/s10845-018-1433-8

Pagliosa, M., Tortorella, G., & Ferreira, J. C. E. (2021). Industry 4.0 and Lean Manufacturing: A systematic literature review and future research directions. Journal of Manufacturing Technology Management, 32(3), 543–569. https://doi.org/10.1108/JMTM-12-2018-0446

Qu, T., Lei, S., Chen, Y., Wang, Z., Luo, H., & Huang, G. Q. (2014). INTERNET-OF-THINGS-ENABLED SMART PRODUCTION LOGISTICS EXECUTION SYSTEM BASED ON CLOUD MANUFACTURING. http://www.asme.org/about-asme/terms-of-use

Rao, N. S. v, Poole, S. W., He, F., Zhuang, J., Ma, C. Y. T., & Yau, D. K. Y. (2012). Cloud computing infrastructure robustness: A game theory approach. 2012 International Conference on Computing, Networking and Communications (ICNC), 34–38. https://doi.org/10.1109/ICCNC.2012.6167441

Sanchez, M., Exposito, E., & Aguilar, J. (2020). Industry 4.0: survey from a system integration perspective. International Journal of Computer Integrated Manufacturing, 33(10–11), 1017–1041. https://doi.org/10.1080/0951192X.2020.1775295

Schlaepfer RC, Koch M, & Merkofer P. (2014). Industry 4.0 Challenges and solutions for digital transformation and use of exponential technologies. https://www2.deloitte.com/content/dam/Deloitte/ch/Documents/manufacturing/ch-en-manufacturing-industry-4-0-24102014.pdf

Sheth Jenis. (2018, July 26). The Industrial Revolution from Industry 1.0 to 5.0! https://supplychaingamechanger.com/the-industrial-revolution-from-industry-1-0-to-industry-5-0/#:~:text=Industry%203.0&text=Around%201970%20the%20Third%20Industrial,to%20further%20automation%20in%20production.&text=Industry%203.0%20introduced%20more%20automated,Programmable%20Logic%20Controllers%20(PLC).

Sushil, P. (2012). Interpreting the Interpretive Structural Model. Global Journal of Flexible Systems Management, 13. https://doi.org/10.1007/s40171-012-0008-3

Tsochev, G., & Sharabov, M. (2021). Artificial intelligence methods used in industry 4.0 in particular industrial control systems. AIP Conference Proceedings, 2333. https://doi.org/10.1063/5.0041610

van Lopik, K., Sinclair, M., Sharpe, R., Conway, P., & West, A. (2020). Developing augmented reality capabilities for industry 4.0 small enterprises: Lessons learnt from a content authoring case study. Computers in Industry, 117. https://doi.org/10.1016/j.compind.2020.103208

Wittenberg, C. (2016). Human-CPS Interaction - requirements and human-machine interaction methods for the Industry 4.0. IFAC-Papers Online, 49(19), 420–425. https://doi.org/10.1016/j.ifacol.2016.10.602

Wollschlaeger, M., Sauter, T., & Jasperneite, J. (2017). The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. IEEE Industrial Electronics Magazine, 11(1), 17–27. https://doi.org/10.1109/MIE.2017.2649104

Wu, T., Blackhurst, J., & O'grady, P. (2007). Methodology for supply chain disruption analysis. International Journal of Production Research, 45(7), 1665–1682. https://doi.org/10.1080/00207540500362138

Xie, W., Xie, L., Zhang, C., Zhang, Q., & Tang, C. (2013). Cloud-based RFID authentication. 2013 IEEE International Conference on RFID (RFID), 168–175. https://doi.org/10.1109/RFID.2013.6548151

Yin, Y., Stecke, K. E., & Li, D. (2018). The evolution of production systems from Industry 2.0 through Industry 4.0. International Journal of Production Research, 56(1–2), 848–861. https://doi.org/10.1080/00207543.2017.1403664

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