The role of industry 4.0 technologies in overcoming pandemic challenges for the manufacturing sector

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Abstract

Industry 4.0 aims to revolutionize the manufacturing sector to achieve sustainable and efficient production. The novel coronavirus pandemic has brought many challenges in different industries globally. Shortage in supply of raw material, changes in product demand, and factories closures due to general lockdown are all examples of such challenges. The adoption of Industry 4.0 technologies can address these challenges and prevent their recurrence in case of another pandemic outbreak in the future. A prominent advantage of Industry 4.0 technologies is their capability of building resilient and flexible systems that are responsive to exceptional circumstances such as unpredictable market demand, supply chain interruptions, and manpower shortage which can be crucial at times of pandemics. This work focuses on discussing how different Industry 4.0 technologies such as Cyber Physical Systems, Additive Manufacturing, and Internet of Things can help the manufacturing sector overcome pandemics challenges. The role of Industry 4.0 technologies in raw material provenance identification and counterfeit prevention, collaboration and business continuity, agility and decentralization of manufacturing, crisis simulation, elimination of single point of failure risk, and other factors is discussed. Moreover, a self-assessment readiness model has been developed to help manufacturing firms determine their readiness level for implementing different Industry 4.0 technologies.

Keywords
industry 4.0, COVID-19, internet of things, cloud computing, cyber physical systems

Introduction

Manufacturing is one of the most affected sectors by pandemics. Coronavirus or COVID-19 is the most recent pandemic infecting people all around the world. According to World Health Organization (WHO), up until June 2021, the number of confirmed cases of COVID-19 patients have reached around 170 million in which around 3.7 million have been passed away (World Health Organization, 2021). This huge number of infected people in such short period of time shows the critical situation that world is currently experiencing. Many countries implemented quarantine rules alongside travel bans to slow down the fast rate of disease transmission. Such restrictions led to limitation in movement of citizens and goods which caused a disruption in supply chain of different products and services (Kumar et al., 2020). Also, due to virus outbreak, demand for certain products which are more crucial at times of pandemic outbreaks have been increased. In many cases, such increase in demand caused operational challenges for different suppliers. Shortage in supply of raw materials and availability of manpower within manufacturing firms were also another two important challenges brought by COVID-19 pandemic.

Figure 1 shows different challenges that faced the manufacturing sector due to the pandemic. Previously, different firms would have estimated a future supply chain considering that material is easily accessible, which COVID-19 pandemic resulted in events that has disrupted supply chains leading to sharp decrease in production. Lee and Wright (2020) emphasized that this interference in the supply chain limited the flow of operations which consequently affected customers. Also, this pandemic showed that industries needed to be more resilient to market

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changes. This can happen by having a factory which is
dynamically responsive through applying real-time insights
on market situation.

COVID-19 pandemic also brought shipping and logistics
challenges which have consequently affected product’s
manufacturing. Air travel ban is one of the most important
factors affecting shipping worldwide which delayed supply
of goods and raw materials to different countries. According
to UNICEF (2020), many airlines are decreasing their
cargo-only flights and try to add more passenger flights to
compensate for losses occurred due to pandemic. Data
shows that the current freight capacity is 25% under the
level recorded for 2019. Also, another barrier in front of air-
freight airlines is an increase in transit time by 3–6 days
which extends the time of supply delivery. However, the
global sea freight rate seems relatively unchanged due to
worldwide implementation of “Blank Sailing.” This specific
practice has its own issues which is tightening the space of
cargo ships due to presence of high volume of Blank
Sailings (UNICEF, 2020).

One of the main reasons that COVID-19 impacted most
manufacturing firms is its place of origin. China is one of the
world’s largest economies which contributes significantly
on global trades. China is a main producer of different
products and components which are crucial for different
industries. As described by Kilpatrick and Barter (2020),
industries such as opto-electronics, bioengineering, and
modern manufacturing are sample examples of industries in
Wuhan which has been all affected by presence of COVID-
19 pandemic. Many companies around the world have
China as their Tier 1 and Tier 2 supplier. Only few of such
industries can properly trace beyond their Tier 1 suppliers
which leads to supply risks. Factories closure in China have
had a domino effect on supply chains of different industries
around the world leading to disruption in manufacturing
(Kilpatrick and Barter, 2020).

Table 1 shows a summary of some examples of COVID-
19 impact on different industries reported in literature.
There are two common challenges which most of the studies
have mentioned. The very first common challenge is the
disruption in supply of raw material which in most cases
decreased the production units within the industry and led to
shortage of supply of different products. The second
common challenge in these studies is the shortage in
manpower due to lockdown implementation around the
world; which in some cases led to full industry closure.

The fourth industrial revolution, known as Industry 4.0
aims to enhance current production methods by im-
plementing different technologies. Internet of Things (IoT),
Cyber Physical Systems (CPS), Additive Manufacturing,
Cloud Based Manufacturing (CBM), and Big Data Anal-
lytics are some examples of technologies used in Industry
4.0 (Muhuri et al., 2019; Tesch da Silva et al., 2020).
Technology implication and transformation to Industry 4.0
showcased a potential positive impact on the manufacturing
sector. As an example, a study performed by Sanders et al.
(2016) investigated the interlinkage between Industry 4.0
and lean manufacturing. The study shows that committing
to Industry 4.0 has a positive impact on lean principles
implementation. A recent study by ABI research (2020)
shows that the deployment of Industry 4.0 solutions in a
manufacturing facility can generate 8.5% in operational cost
saving on yearly basis (Bonte et al., 2020).

Pandemic challenges on the manufacturing sectors can
be tackled by implementation of different Industry 4.0
technologies. One of the most prominent Industry 4.0
technology that is being widely used at times of pandemics
is Additive Manufacturing (AM). The sudden surge in
demand for Personal and Protective Equipment (PPE) and

Figure 1. Different challenges brought by pandemic on manufacturing firms.
shortage in supply of such products was the reason of increasing popularity of AM. Tareq et al., (2021) provided an overview on AM and its impact on solving challenges of COVID-19. Their paper also found that many manufacturers in AM community have already taken initiatives and increased their production capacity to produce face shields, face masks, ventilators, and nasopharyngeal swabs using AM techniques (Tareq et al., 2021). CPS is considered a vital Industry 4.0 technology that can be instrumental at times of pandemics. CPS technologies include computer simulations, big data analytics, blockchain, and cloud computing. Computer simulations can mimic responses of actual systems to events that occur at times of pandemics. Contingency plans can be developed based on the results of computer simulation. Big data facilitates a transparent infrastructure in which firms can use this data to ensure supplies availability, improve product quality, and analyze data using machine learning and neural network to predict consumer behavior and needs. These gathered data can also assist the production assessment tools which identify the performance gaps (Sílvêrio et al., 2020). Blockchain technology is very effective in raw material provenance identification and counterfeit prevention. Cloud computing facilitates collaboration, computational elasticity, e-trade, and Business-to-Business (B2B) distant sales (Dertouzos et al., 2020). The inclusion of cloud computing into manufacturing is often referred to as Cloud Manufacturing which results in services that are in line with user’s requirements (Zhu et al., 2019).

Table 1. Literature review on challenges of COVID-19.

| Author (s)             | Studied sector | Contribution                                                                                                                                 |
|-------------------------|----------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| (Pu and Zhong, 2020)    | Agricultural sector | The paper discussed the impact of COVID-19 on agriculture production sector in China. Shortage of labor, disruption in sales channels, and loss in harvest are considered as main contributing factors to such problem. |
| (Majumdar et al., 2020) | Textile industries | The study showed the impact of COVID-19 on textile supply chain and clothing industry. The paper discussed the importance of China and its effect on clothing supply chain all around the world since China is considered as main supplier for different materials such as synthetic fibers, polyurethane tapes, and dyes. |
| (Kumar et al., 2020)    | Various industries | The paper studied general reasons contributing to supply chain disruption due to COVID-19. Weakened and increased demand for different goods, failure in raw material supply, shipping and delivery blockages, and reduced workforce were counted as such contributing factors leading to disruption in supply chain. |
| (Gebreslassie, 2020)    | Energy sector   | The author focused on the energy sector in African countries and how COVID-19 has impacted the energy access. It has been mentioned that African countries rely heavily on imports from other countries for renewable energy technologies in order to satisfy the local demand. COVID-19 pandemic had negative impact on renewable energy sectors in Africa since, alongside with worldwide trade restrictions, the source countries for the renewable energy technology such as China, and USA have shifted their focus toward dealing with pandemic. This issue consequently placed many jobs at renewable energy sectors in African countries at risk. |
| (Shafi et al., 2020)    | Medium-sized enterprises | The paper discussed the impact of COVID-19 on Pakistan’s medium sized enterprises and economy. Reports have shown that Pakistan’s exports have been plunged by 50% due to COVID-19 which decreased the total revenue of the country by one third. Factories closure due to lockdown implementation in Pakistan had also an impact on Pakistan’s economy in which only 50 out of 2700 factories remained working during lockdown in Karachi. |
| (Rowan and Laffey, 2020) | Personal and protective equipment manufacturing firms | The study reviewed the impact of COVID-19 on supply chain of Personal and Protective Equipment (PPE) around the world and Republic of Ireland in more specific. In order to fight the shortage of PPE, the study found that implication of technology can possibly increase the production sustainability in a way that meets the demand of certain product. |
| (Sharma et al., 2020)    | Various industries | The paper took a unique approach in order to observe the impact of COVID-19 on NASDAQ 100 firms by looking into the tweets that these firms have posted on Twitter. The paper found that NASDAQ 100 firms are facing demand and supply challenges. Hence, these companies are looking into building a more resilient supply chain by implementing the latest technology. |
There are several research papers in literature that discuss Industry 4.0 technologies implications on solving pandemic challenges. Javaid et al., (2020) have discussed applications of 9 different Industry 4.0 technologies that help in solving pandemic challenges related to healthcare system and disease contamination. Moosavi et al., (2021) performed a comprehensive literature review on definition of Industry 4.0 technologies and provided a case study which shows how these technologies can help in developing a mobile application which contributes to pandemic management. Acioli et al., (2021) investigated the benefits of Industry 4.0 technologies for achieving sustainable supply chains at times of pandemics. Their paper discussed generally the Industry 4.0 benefits and identified the opportunities and challenges related to the implementation of Industry 4.0 technologies in supply chain. Kumar et al., (2020) performed a literature review about COVID-19 operational challenges on retailers. They have discussed which Industry 4.0 technologies can overcome challenges mentioned and further proposed a roadmap for Industry 4.0 implications for COVID-19 (Kumar et al., 2020). Lepore et al., (2021) investigated the readiness and responsiveness of different Italian regions to accelerate sustainable manufacturing by implementing Industry 4.0 technologies. Their work is holistic and comprehensive, but it does not focus on manufacturing firms in specific.

The adaption of Industry 4.0 technologies is very important to face future pandemics. The degree of adaptation to Industry 4.0 can be measured using “Maturity” and/or “Readiness” models. The fundamental difference between these two models as mentioned by Schumacher et al. (2016) is that maturity model measures the maturity of an industry regarding specific target whereas readiness model facilitates the development process. Many papers exist in literature on maturity models for Industry 4.0 implementation. Work done by Caiado et al. (2021) is an example of such models in which the authors developed a fuzzy rule-based maturity model for Industry 4.0 implementation on supply chain management. Colli et al. (2018) has also developed an enhanced maturity model which contains company-specific assessment. However, very limited work has been done on readiness models. Pacchini et al. (2019) developed a model to measure the degree of readiness for the implementation of Industry 4.0 technologies based on the Society of Automotive Engineers (SAE) standard to measure the readiness for implementing the lean manufacturing principles in a company. The model is basic and does not account for interrelations among enabling technologies. It also gives all enabling technologies the same weight. Another readiness model available in literature is the University of Warwick’s Industry 4.0 readiness assessment tool (Agca et al., 2017). University of Warwick’s readiness tool compromise of six core dimensions, 37 sub-dimensions, and readiness level descriptions. Although the University of Warwick’s readiness tool is comprehensive, it does not provide information on readiness for each Industry 4.0 technology since the outcome of this tool is only the overall Industry 4.0 readiness based on defined dimensions and sub-dimensions.

Based on the literature review, it is observed that more focused research has to be done on the implementation of Industry 4.0 technologies in manufacturing firms to overcome pandemic challenges. In addition, new tools to assess the readiness for Industry 4.0 transformation are needed. The aim of this work is to represent and discuss how different Industry 4.0 technologies can help the manufacturing sector overcome pandemic challenges. The technologies presented in this work are CPS, Additive Manufacturing, IoT, Industrial and Autonomous Robots. Moreover, an easy to use assessment method in which manufacturing firms can use to measure their readiness level for implementing Industry 4.0 technologies is developed and implemented on a case study. The proposed readiness model asks definitive questions from industry owners to ease the assessment procedure and uses a simple weighting technique for different technology categories. The suggested readiness model will assist decision makers to gain understanding about their degree of readiness for transformation to Industry 4.0 which can subsequently lead to better crisis management in future.

**Solutions to Pandemic Challenges by Implementation of Industry 4.0 Technologies**

Implementation of Industry 4.0 technologies into different industries can possibly overcome challenges brought by COVID-19 pandemic. The possible role of Cyber Physical Systems (CPS), Additive Manufacturing, Internet of Things (IoT), and Industrial and Autonomous Robots at times of pandemic are discussed in this section.

**Cyber Physical Systems**

Cyber Physical System (CPS) refers to a system that combines computational analysis with physical objects. In other words, CPS uses computers to monitor physical processes and make necessary changes while examining the environment. This examination is made possible by consistent real-time data collection and processing. CPS has three fundamental layers named as Physical, Synergic, and Cyber Layer. Physical layer is the machine or physical equipment that is being used. Synergic layer consists of sensors and other required equipment for real-time data collection of processes that are taking place within the industry. Cyber layer involves programming and software which facilitate communication between different layers. Another important contribution of Cyber layer to CPS is the analysis of data collected from Synergic layer (Ahmed et al., 2019). CPS itself can consist of different Industry 4.0
technologies such as Simulation, Big Data Analytics, Cloud Computing, and Blockchain. These technologies work hand in hand to process data and deliver feedback to the physical system based on the analysis made.

CPS technologies have the flexibility of working individually or simultaneously together to solve a challenge faced by pandemics. For example, several CPS technologies can be used for generating an algorithm to predict market behavior and resource availability at times of pandemic. The predictive algorithms can be made using Big Data Analytics and maintained by Blockchain and Cloud Computing. Predictive analytics is a type of analytics problem which provide a foresight about the future based on historic and current data available to the firms (Belhadi et al., 2019). Statistical analytics and knowledge-discovery oriented techniques are two categories of predictive analytics. The first category uses mathematical models such as regression techniques, K-nearest neighbor (KNN), and Bayesian to analyze available data. The second category implements machine learning methods such as Multiple Backpropagation (MBP), Neural Networks (NN), and Self-Organizing Map (SOM) to analyze data and predict future events (Belhadi et al., 2019). In context of overcoming pandemic challenges, with the help of Big Data Analytics, various real case scenarios of crisis happening around the world can be analyzed in which the demand and supply can be studied in more depth. These data can be then combined, and a predictive algorithm can be developed. Response of different industries and market change due to COVID-19 pandemic can provide an ample amount of data to be analyzed to create the predictive algorithm for future pandemics. These algorithms created can be then simulated with help of different softwares in order to predict the future of an industry at times of pandemic. Computer simulations are part of digital twin technology that aim to provide a digital representation for a physical environment (Madni et al., 2019). Different types of simulations such as discrete event simulations and agent-based simulations are used to observe the behavior of virtual production floors in a what-if simulation modes (Madni et al., 2019). Next, Blockchain and Cloud technologies can help in preserving and further expanding the developed algorithms. Cloud manufacturing enables global collaboration between the firms (Lu and Xu, 2019). In addition to enabling algorithm sharing between firms, Cloud Computing also provides storage for storing algorithms. The algorithm generated help firms to gain more understanding about different aspects of their production in future pandemic outbreaks. In details, the algorithm can predict which of their products’ demand will surge, which raw materials will have shortage, and what will be the production rate during lockdown implementations. Figure 2 illustrates algorithm generation steps.

Computer simulations. Computer Simulation is a technology that uses algorithms to make predictions about possible outcomes for different case scenarios (Bai et al., 2020). The rise of real-time data collection and cloud technologies forced simulations to transform from static to dynamic environment. Different scenarios can be simulated based on different variables. These variables can vary from machines conditions to labor issues and resources restriction (Da Silva et al., 2020). Key features of computer simulations which can be helpful at times of pandemic are:

- Crisis Simulation: Simulation of different manufacturing processes and systems can help industries to have better control over their resources represented by material resources, people, money, and knowledge at times of pandemics. Computer simulations can mimic responses of actual systems to events that occur at times of pandemics. Shortage of raw material, lack of manpower, and drastic increase in demand for certain products are among the major events that occur during pandemics. Manufacturing companies can develop contingency plan based on the results of crisis simulation.
- Product Development and Modeling: At times of pandemic, demand for certain new products increase; that is, Personal and Protective Equipment (PPE), and
ventilators. Many factories that do not originally manufacture these products have modified their production lines to start producing new types of products that are in high demand during the pandemic. Computer simulation can be used in the product development phase to design new products using finite element simulation. The production system can be simulated using discrete event simulation based on stochastic modeling. Hence, implementing Computer Simulation technology into industries can possibly reduce the product development time, raw material usage, and faulty production costs while increasing the overall quality of the manufactured product.

**Big data analytics.** Large volume of structured, semi-structured, and unstructured data from different sources can be organized and analyzed using Big Data Analytics to help manufacturing companies and enterprises take the right decisions during pandemics. Manufacturing firms cannot operate in isolation from their vendors, sub-assembly suppliers, and customers at times of pandemic. Big data facilitates a transparent infrastructure in which firms can use this data to ensure supplies availability, improve product quality, and analyze data using machine learning and neural network to predict consumer behavior and needs. The main features of Big Data Analytics that can be helpful at times of pandemic are:

- **Data Mining and Analysis:** This feature involves the collection, organization, and analysis of data obtained internally and from sources outside manufacturing firms. Real-time data acquisition from the factory floor and from different vendors and sub-assembly suppliers can be collected and organized. Different types of content that include text and data from internal and external documents, webpages, social media, and content from audio, video, and imagery can also be collected, organized, and analyzed. Different patterns in market demand and supply and forecasting of future demand can be obtained based on the content collected from internal and external sources using machine learning and neural network.
- **Transparency:** Faults in the production line can be captured instantly from real-time data acquisition to prevent waste. Any interruption in the supply chain can be detected at the very early stages. Alternative supply strategies can be implemented to avoid shortage in raw material, spare parts, or lack of equipment.

**Blockchain.** Blockchain is a special type of database in which data is stored in blocks that are chained together in a chronological order to form a chain of data named “Blockchain.” Blockchain sits below a distributed ledger to validate and verify the transactions in the ledger by producing a new block to the chain (Rutland, 2017). Immutability and transparency, disintermediation, irreversibility, and automation are important features of blockchain technology. Blockchain technology proved to be a reliable way to store data about monetary transactions. The main features of this technology that can be helpful for manufacturing firms at times of pandemic are:

- **Immutability and Transparency:** Immutability implies that data cannot be edited or deleted after it has been created. Due to the shortage in material supplies during COVID-19 pandemic, material provenance and counterfeit became a major issue for many manufacturers. Manufacturing firms can use blockchain to record the origins of the material they purchased and verify its authenticity. Ledgers can be connected across the whole supply chain to track material supplies. Blockchain technology can also help manufacturers execute transactions with high transparency, high speed, and lower fraud risk. It promotes end to end visibility with a permanent digital record of materials, sub-assemblies, and products.
- **Automation:** Smart contracts are self-executing contracts that are very effective at times of pandemics. Self-executing contracts are computer codes in which the terms of agreement between different parties are embedded into the code that is loaded on a distributed, decentralized blockchain network. Smart contracts execute when the terms and conditions are met. Smart contracts offer faster solution to execute transactions in the supply chain at times of pandemic. They eliminate the need for intermediaries and manual document processing. In addition, the risk of single point of failure is eliminated since the contract is distributed across multiple locations in the network.

**Cloud computing.** Cloud computing is the delivery of computing services over the internet. The three components of cloud technology are Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). Some useful key features of Cloud Computing that can be helpful for manufacturing firms at times of pandemic are:

- **Collaboration:** Collaboration is made easier using Cloud Computing. Productivity and communication presented a challenge for many manufacturing firms due to remote work restrictions. Cloud Computing gives the ability to remote workers to access, review, and edit any type of files such as documents and CAD files in real-time. Product development teams can work without interruption during pandemics using cloud collaboration. The collaborative environment
maintains efficiency and productivity even if the employees are at multiple locations.

- Elasticity: Cloud elasticity is the process by which Cloud Computing resources can be provisioned dynamically without human interaction based on the process needs. Additional storage, database instances, virtual machine instances can be added in response to increased business demand or workload changes during pandemics without any kind of interruption or down time. As a result, business continuity is guaranteed.

**Additive Manufacturing**

With help of this technology, computer-made 3D models can be created through placing consecutive layers of material. To manufacture a component using additive manufacturing, the model should be 3D designed, printed, and post processed if required. The post processing step usually consists of machining, heat treatment, polishing, and painting (Srivastava et al., 2021; Thompson et al., 2016). The important characteristics of Additive Manufacturing which can help solving pandemic challenges are:

- Agility: Using Additive Manufacturing technology, industries can faster develop new products or revise the design of existing products due to the fact that this process is mold-less and fixture-less. On demand production, reduction in product’s lead time, faster response to market demand, and ease of decentralizing production are all advantages of Additive Manufacturing which lead to a more agile production environment (Arora et al., 2021). Assemblies produced using traditional manufacturing processes can also be consolidated into a single additively manufactured component which saves time and effort.

- Flexibility: Freedom in design is one of the important aspects of this characteristic. Design freedom can help in producing modified products such as enhanced face shields, mask holders, and ventilators which are crucial at times of pandemics with minimum level of effort comparing to traditional manufacturing processes. Another aspect of this feature is reducing the dependency of industries to products’ supply chain by providing alternatives in production and reducing the manufacturing steps. One challenge that has been discussed earlier was the interruption in shipments of raw materials or components to be assembled in the final product. With the flexibility that Additive Manufacturing provides, industries can re-design certain products so that they can be produced using Additive Manufacturing methods while minimizing reliance on other suppliers. As a result of this feature, industries can continue producing albeit the drastic decrease in supply of raw materials and important counterparts.

**Internet of Things (IoT)**

The term “Internet of Things” has first been used by Kevin Ashton (2009) to introduce the new idea of Radio Frequency Identification Technology (RFID) in Proctor and Gamble’s supply chain. Hence, initially Internet of Things (IoT) was known as a technology that help in tracking different products (objects) within different manufacturing stages. The idea of IoT evolved to be described as a tool that connects physical to digital world. This linking between two different worlds become possible by use of transducers and sensors. The objects within IoT frame are characterized into four main groups of Trackable Objects, Data Objects, Interactive Objects, and Smart Objects. Trackable and Data Objects are objects that contain simple RFID chip to provide information about the location or current state of the product. Interactive Objects gather information using sensors and respond to the situation using actuators. Finally, Smart Objects are identified as things that can perform certain degree of data processing and act upon the situation with help of transducers (Greer et al., 2019). RFID technology and Wireless Sensor Networks (WSN) are among the important IoT technologies that can help at times of pandemic.

**Radio frequency identification (RFID) chip technology.** RFID technology is considered as core of IoT (Prasad, 2020). RFID technology uses wireless transmission between a tag and reading device to track and classify objects (Bai et al., 2020). To identify the position of an object and obtain information on the tag, reader releases a signal using an antenna. The RFID tag then receives this signal using the built-in receiver and responds to the signal using the transmitter. The antenna collects the signal received by the tag and then transfers it to the reader. Finally, the reader transmits the information received to the computer for further analysis (Urso et al., 2020). The three types of RFID tags with an embedded Integrated Circuit (IC) are active, passive, and semi-passive tag which vary in their connection range (Urso et al., 2020). Chipless RFID sensors are other type of tags which use electromagnetic signature of the tag to identify information and make the communication possible with the antenna using a resonant circuit (LC) (Min et al., 2020; Vena et al., 2012). RFID technology traits that can help at times of pandemics are:

- Object Tracking: Object Tracking is an important characteristic of RFID technology that can provide useful information to manufacturing firms’ executives. Imposing lockdown restrictions during pandemics result in reduced number of workforce available which consequently lead to a decrease in production line monitoring. Hence, object tracking within inter-organizational levels can improve production lines supervision by syncing the object automatically to the IoT based machinery which makes
remote product monitoring possible. Moreover, it has been discussed that disruption in supply chains and lack of communication between different firms resulted in unsuccessful delivery of products. With help of RFID, product deliveries and shipments can be precisely tracked which leads to improved transparency for industries and customers.

- Production Lines Alteration: With help of this trait, industries can have a more dynamic production lines in which certain products can be mass produced if needed. In pandemics, sudden and unexpected rise in demand of certain goods and products lead to poor response from the industries in terms of meeting the demand. It is known that Reconfigurable Manufacturing Systems (RMS) can help firms to be more responsive to the market demands (Dou et al., 2020). With help of RFID technology, industries which produce several products can adjust their production units and machines to respond to the increase or decrease in demand for certain goods. Current developments in technology of RFID and IoT led to development of industrial machines which are capable of real-time interaction with the product containing RFID tag (Siemens, 2013). This interaction can help in producing several types of products using single set of machinery. At times of pandemics, this trait enables industries to easily change product produced on the same production line so that most of the production units are operating for the product that has high demand.

Wireless sensor networks (WSN). Wireless Sensor Networks (WSN) is an important concept in IoT which describes group of sensors working together to form a unified network of sensors. WSN mainly consist of single or multiple base stations, and several sensor nodes (Li and Kara, 2017). In industries, WSN and RFID technology work together and simultaneously to achieve the required outcome. From physical perspective, WSN nodes contain different components to sense, collect, and process data. Within WSN, sensors are responsible to sense the changes in the environment. Sensors produce analog signals which are then converted by digital converters to digital signals which can be interpreted by processors for further analysis. Processors are components which are responsible for processing signals obtained from sensors and controlling other components in the sensor node. Lastly, a transceiver connects the sensor nodes to the network allowing connections to be made. Power sources are also needed to be placed in sensor networks to cover the power consumed within the system. One of the major considerations for industries using WSN is the possible signal interference from other devices. This noise can affect signal strength leading to errors in data collection and analysis (Gungor and Hancke, 2009). The important features of WSN that can help in pandemics are:

- Connection Enabler: WSN is a group of sensors working together to sense a given environment. Previously it has been discussed that how implementation of RFID technology within manufacturing firms can change and adapt production lines to given circumstances. Having RFID chip on products solely cannot make any changes possible. Hence, group of sensors are used to interpret with RFID tags on each product at different stages of manufacturing. This interaction between sensors and tags helps firms in two ways. First, it leads to synchronization between different industrial machinery within one production line to create a more dynamic production environment. Second, being able to sense the environment consistently, leads to real-time data transfer which can facilitate the flow of information between different departments within one firm, that is, logistics and production. As an example, an information on disruption in production line will be immediately sent to logistics unit which allows the unit to take required actions in terms of product distribution and inventory management to satisfy the products’ demand.

- Feedback Provision: WSN enables real-time data collection which can be used in obtaining feedback. Feedback provision can be beneficial specially at times of pandemics in which industries opt to produce new products to meet the market demand. Hence, constantly obtaining feedback from the production line for the new products can detect any faults existing in the production line and possibly prevent high product defect costs.

Industrial and Autonomous Robots

According to International Organization for Standardization (ISO), industrial robot is an automatically controlled robot which has multi purposed functionality and the ability to be reprogrammed if needed. Such robots are categorized based on their structure and axis of rotations. One important aspect to industrial robots is their degree of collaboration with workers. Some industrial robots are able to respond to the movement of worker in real-time using sensors, this represents the maximum degree of collaboration. Whereas some industrial robots are needed to be completely separated from workers in the workshop (International Federation of Robotics IFR, 2019). Unlike industrial robots which require human interventions, autonomous robots are built to perform tasks autonomously. Varied in different sizes and functionality, the two most important aspects of autonomous robots are their degree of autonomy and artificial intelligence. Technology advancements led to creating robots with high level of intelligence which have human-like capabilities in performing different tasks (Fitzgerald and Quasney, 2017). The key features of
Industrial and Autonomous Robots that are helpful at times of pandemic are:

- Remote Controlled: An example of remote-controlled robots are the robots being used in hazardous production environment where humans are not permitted to enter (Liu and Wang, 2020). Such remote-controlled robots can be also used at times of pandemics when the lockdown restrictions are applied. Implication of these robots enable workers to remotely control different industrial robots within the firm and continue production albeit the restrictions brought by pandemics.

- Autonomy: At times of pandemics, disruptions in goods and services delivery will occur. Hence, swarm of autonomous robots can help manufacturing firms in logistics and delivery of the goods and services. For short distance deliveries, aerial robots such as drones can become helpful to solve the issue. Currently, drones are being used in parcel delivery firms, and they already had a positive impact into businesses which showcases the positive future for drone technology implementations in different industries (Pugliese et al., 2020). Due to current COVID-19 pandemic, the Autonomous Delivery Robot (ADR) technology has also gained more popularity since it can provide contactless delivery which adheres to social distancing practices (Pani et al., 2020). The autonomy feature in such robots will ensure a safe and successful product delivery to the desired destination.

Table 2 showcases the contribution of different Industry 4.0 technologies to solve pandemic challenges.

**Readiness model methodology**

In this section, a self-assessment model is proposed for manufacturing firms to measure their readiness level with respect to transforming to Industry 4.0. The main reason of doing such assessment is to get feedback on current infrastructure state of the firm, and to determine in which area (technology) the firm must invest. The readiness model proposed in this section can be counted as starting point for different firms to gain more insight on requirements needed to implement different Industry 4.0 technologies. As mentioned earlier, currently there are two widely used models called “Maturity” and “Readiness” models which determine an industry’s degree of adaptation to Industry 4.0. Maturity model determines industry’s degree of development with respect to certain goal whereas Readiness model measures how far or close an industry is to start implementing Industry 4.0 components as whole (Schumacher et al., 2016).

The model proposed in this section is designed and structured in a way which reduces complexity and helps different manufacturing firms to assess their Industry 4.0 adaptability by answering sets of questions and assigning weight for each technology. The model asks discrete questions which remove possible biases that might take place in one’s answer while providing score for technologies’ state. The questions are designed based on a set of requirements or prerequisites for the implementation of each technology. Moreover, in order to account for operational variations within different manufacturing firms, this model also requests firm owners to assign weight for each technology based on the technology’s importance for the firm.

For every Industry 4.0 technology that has been described in previous section, a set of requirements have been assigned which contain number of questions the manufacturing firm has to answer. The answer for each question can be in either format of “yes” or “no” where for every “yes”, one point will be added and for every “no” answer, zero point will be given. After responding to all the questions for each Industry 4.0 technology and obtaining the final score in terms of points, the weight for each technology is assigned by the responder. The value of weight assigned for respective technology varies from zero to one in which the total weight for all four categories of technologies must not exceed one. Finally, the readiness score and weighted readiness for each technology can be calculated using equations (1) and (2) as below:

$$R_n = \frac{\sum_{i=1}^{m} Q_{ni}}{Z_n}$$

(1)

$$WR_n = W_n \times \frac{\sum_{i=1}^{m} Q_{ni}}{Z_n}$$

(2)

Where $Q_{ni}$ is the point obtained from the corresponding question available for technology “n.” $Z_n$ is the maximum number of points possible for the technology of interest. $R_n$ is the readiness score of the technology “n.” $m$ is the number of questions available for each technology of interest. Lastly, $W_n$ and $WR_n$ correspond to weight assigned and weighted readiness score for the technology “n,” respectively.

The calculated readiness score ($R_n$) is used to indicate the readiness of the firm to implement certain Industry 4.0 technology regardless of the weight and importance of technology. This score is further used in developing a radar diagram to visualize the results for manufacturing firm owners. On the other hand, the weighted readiness score ($WR_n$) accounts for the assigned weight and importance of the technology within the firm which is used to calculate the total readiness score ($R_t$) for the manufacturing firm of interest.

Sets of questions to determine firm’s readiness score in different Industry 4.0 technologies have been represented in Figure 3.

In order to measure the readiness of a firm to implement CPS technologies, four important requirements are
The requirements are Data Acquisition, Security, Connectivity, and Infrastructure. To analyze data and predict consumer behavior, the firm has to be able to acquire reliable data from different sources at first place. Moreover, digitalization can bring possible cybersecurity concerns which firms have to be able to address. Being able to make suitable connection among the firm and having proper infrastructure for implementing CPS technologies are also important aspects in determining an industry’s degree of readiness for implementing CPS technologies.

To measure the readiness of a firm to implement Additive Manufacturing technology, four important requirements are considered. The requirements are 3D printing/modeling, skilled workers, post treatment equipment, and raw material supplies. Presence of suitable high speed 3D printers, skilled workers that can operate such printers, and 3D modeling software are crucial for agility in production. In many cases, 3D printed components require post treatment actions to enhance printed component. Hence, the firm should also acquire post treatment equipment and machinery which are needed to obtain final product.

To measure the readiness of a firm to implement Internet of Things technology, three requirements are considered. The requirements are Infrastructure Availability, Data Monitoring, and Skilled Workers. The very first requirement is availability of infrastructure for digitizing the industry. Being able to perform real-time data monitoring is another requirement which industries have to consider. Implementing IoT also requires presence of skilled workers who can work with IoT devices.

Industrial and Autonomous Robots can play a significant role in solving pandemic challenges within the firm. Implementing robots within a manufacturing firm requires investment in infrastructure which companies have to be aware of. Presence of skilled workers who can operate and perform regular maintenance for the robotic systems is also another factor. Lastly, COVID-19 challenges further emphasized the importance of autonomy in robots which is ability to perform tasks autonomously without human interference.

After answering all questions and obtaining the weighted degree of readiness for each technology, the total readiness percentage can be calculated using equations (3) and (4) below:

Table 2. Different technologies contribution and traits.

| Technology     | Contribution                                                                 | Description                                                                                                                                 |
|----------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| CPS            | • Crisis simulation                                                          | Helps in simulating different crisis case scenarios which can provide a better preparation for future pandemics. Also, this technology can be used in modeling new products using finite element simulations. |
|                | • Product development and modeling                                           |                                                                                                                                              |
| Big data       | • Data mining and analysis                                                   | Using this technology allows manufacturing firms to analyze data gathered at times of pandemic to predict market patterns at times of pandemic. Additionally, this technology can be used to interpret with real-time data acquired from production floor to provide more transparency in the production. |
| analytics      | • Transparency                                                               |                                                                                                                                              |
| Blockchain     | • Immutability and transparency                                              | Blockchain technology can help in maintaining data security and providing more transparent communication across the supply chain. Moreover, this technology provides a faster transaction method in supply chain by means of self-executing contracts which remove the need for intermediaries. |
| Cloud computing| • Collaboration                                                             | Implementation of cloud computing can help industries to better collaborate with one another which is crucial at times of pandemic. Cloud computing can also ensure the continuity of businesses due to its ability to dynamically expand resources whenever needed. |
|                | • Elasticity                                                                 |                                                                                                                                              |
| IoT            | RFID technology                                                              | Apart from usage in tracking different parts among the industry, RFID technology can also help in facilitating production for certain highly demanded goods which are crucial at times of pandemics. Having production lines that can interpret with RFID tags will lead to producing variety of products using similar sets of equipment. |
|                | • Object tracking                                                            |                                                                                                                                              |
|                | • Production lines alteration                                                 |                                                                                                                                              |
| WSN technology | • Connection enabler                                                         | Wireless sensor networks act as a bridge between production line and different CPS and RFID enabled devices. Hence, in order to get use of other technologies to solve challenges brought by pandemics, WSN technology must be implemented to enable connections which results in faster command executions. This technology can also help in feedback provision to prevent possible manufacturing defects that might be appeared while producing certain new product. |
|                | • Feedback provision                                                         |                                                                                                                                              |
Figure 3. Industry 4.0 readiness survey.
\begin{align*}
R_t &= \sum_{n=1}^{k} WR_n \\
\%R_t &= R_t \times 100
\end{align*}

Where \( k \) is total number of technologies. \( R_t \) and \( \%R_t \) are the degree of total readiness and percentage degree of total readiness of the firm, respectively.

The calculated percentage for total degree of readiness for a firm is used to determine the readiness level of the given firm. Readiness level indicates how ready the manufacturing firm is for implementing Industry 4.0 technologies. The scale consists of five levels as shown in Figure 4. The lowest level that firm can be placed in is level zero, whereas the highest possible level is the level four. Higher levels mean that the firm is more prepared for implementing different Industry 4.0 technologies such as IoT, CPS, and Additive Manufacturing. Table 3 provides the evaluation for every readiness level proposed in this model.

To showcase how above method works in real-life situation, the survey has been answered by a representative from an aluminum extrusion factory in Jordan. For every “yes” answer to the question, a point has been awarded to the firm whereas for every “no” answer, no points have been allocated. Furthermore, subjective weights were assigned for each category based on the expert’s opinion. The fixed-point allocation method is used in which the percentage of points added should be equal to 100%. Results obtained have been tabulated in Table 4 which is later followed by a radar chart Figure 5 to provide better visualization for industry’s readiness for each technology.

After obtaining the degree of readiness for each technology, the total readiness percentage can be calculated using equations below:

**Table 3. Readiness level index.**

| Readiness level | Category       | Evaluation                                                                 | Percentage readiness range |
|-----------------|----------------|----------------------------------------------------------------------------|-----------------------------|
| 0               | Not prepared   | The firm has high deficiency in infrastructure and skilled workers.         | 0<\%R_t<20                 |
| 1               | Primary        | There is an evidence of limited availability of infrastructure and skilled workers within the firm. | 20<\%R_t<40                |
| 2               | Intermediate   | The firm is correctly working toward Industry 4.0 technologies implementation. | 40<\%R_t<60                |
| 3               | Progressive    | The firm has advanced knowledge and infrastructure but requires few adjustments and investments. | 60<\%R_t<80                |
| 4               | Prepared       | The firm is fully prepared to transform to Industry 4.0.                     | 80<\%R_t<100               |

**Table 4. Case study results.**

| Category                        | Cyber physical system | Additive manufacturing | Internet of things | Industrial and autonomous robots |
|---------------------------------|-----------------------|------------------------|--------------------|----------------------------------|
| Total number of questions per category (Z) | 5                     | 6                      | 9                  | 4                               |
| Number of questions that have been answered “yes” | 2                     | 3                      | 4                  | 2                               |
| Weight assigned for the category | 0.3 (30%)             | 0.1 (10%)              | 0.2 (20%)          | 0.4 (40%)                       |
| Calculated \( R_n \)            | 0.4                   | 0.5                    | 0.44               | 0.5                             |
| Calculated \( WR_n \)           | 0.12                  | 0.05                   | 0.088              | 0.2                             |

**Figure 4. Readiness level scale.**
The radar chart for this case study which is based on the readiness score (Rn) implies that this firm is more prepared to adopt to some technologies than others. Additive Manufacturing is one such technology which the firm scored 0.50 which shows that the firm is half-way prepared to implement Additive Manufacturing within its firm. On the other hand, the firm scored 0.4 on Cyber Physical Systems technologies which shows that the firm has to invest more in development of this technology within its firm. Additionally, using the weighted readiness score, the manufacturing firm has scored total readiness percentage of 45.8% which according to the Figure 4 scale, the firm is placed at Intermediate stage of Industry 4.0 readiness. This stage reflects that the firm is working toward Industry 4.0 technologies implementation but still needs more investment in Industry 4.0 technologies.

\[ R_{t} = \sum_{n=1}^{k} WR_n = 0.12 + 0.05 + 0.088 + 0.2 = 0.458 \]

\[ \%R_{t} = R_{t} \times 100 = 0.458 \times 100 = 45.8\% \]

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**Conclusion**

It is shown in this work that the application of Industry 4.0 technologies can be instrumental in overcoming COVID-19 pandemic challenges. Industry 4.0 technologies can be useful at times of pandemics in the following major areas:

- Crisis simulation: Computer simulations can mimic responses of actual systems to events that occur at times of pandemics. Contingency plans can be developed based on the results of computer simulation.
- Transparency: Big data facilitates a transparent infrastructure in which firms can use data obtained from different sources to ensure supplies availability, improve product quality, and analyze data using machine learning and neural network to predict consumer behavior and needs.
- Immutability and Automation: Blockchain technology is very effective in raw material provenance identification and counterfeit prevention due to the immutability and transparency, disintermediation, and irreversibility that this technology provides.
- Contracts execution automation: Smart contracts loaded on a distributed, decentralized blockchain network offer faster solution to execute transactions at times of pandemic. They eliminate the need for intermediaries, manual document processing, and prevent single point of failure since the contract is distributed across multiple locations in the network.
- Collaboration and business continuity: Cloud computing proved to be very effective for remote workers at multiple locations to collaborate in real time through accessing, reviewing, and editing any type of files such as documents and CAD files in real time. Cloud computing can ensure business continuity by adding storage, database instances, and virtual machine instances in response to increased business demand or workload changes during pandemics without any kind of interruption or down time.
- Agility and decentralization of manufacturing: As Additive Manufacturing is mold-less and fixture-less, it expedites product development process and manufacturing. In addition, Additive Manufacturing facilitates decentralized and localized production which is advantageous at times of pandemics.
- Autonomous delivery: Autonomous delivery robots can provide contactless delivery of goods which adheres to social distancing practices. Drones,
autonomous cars and trucks are samples of autonomous delivery robots.

Moreover, a self-assessment readiness model that identifies the prerequisites for each Industry 4.0 technology has been developed and implemented on a case study to measure the readiness of manufacturing firms to implement Industry 4.0 technologies.

Future work that can be carried out is reviewing the current implementations of different Industry 4.0 technologies within variety of manufacturing firms and showcasing their positive impacts on manufacturing firms by means of quantitative approaches. Moreover, in terms of Industry 4.0 implications, a framework can be developed which would assist manufacturing firms to transform to Industry 4.0 and upgrade their state of production.

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