Address business crisis caused by COVID-19 with collaborative intelligent manufacturing technologies

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Abstract: While COVID-19 has affected the daily life of almost everyone around the world, it has also caused major disturbances to the global economy and to the operations of many businesses in the manufacturing industry. Regional lockdowns resulted in supply chain breakages. Workforce shortages caused difficult shop floor operations. This study tries to discuss how collaborative intelligent manufacturing technologies can help to address these challenges through (i) optimal design of resilient collaborative supplier networks; (ii) collaborative planning of manufacturing operations among geographically distributed manufacturing plants; (iii) functional redundancy and dynamic reconfiguration of different shop floors; (iv) dynamic intelligent rescheduling of workforces for factory/shop floor operations; (v) remote testing and maintenance of manufacturing equipment with the support of digital twins technologies. These approaches are expected to be an effective hedge against the impact of COVID-19 or other natural disasters.

1 Introduction

The COVID-19 pandemic has caused an unprecedented human and health crisis. The COVID-19 is highly infectious, has no effective drugs, has many severe patients, and consumes a lot of medical resources. At the same time, it is creating major disturbances to various business operations and harming the global economy \cite{1}. The production, logistics, and consumer activities have been affected to varying degrees.

To fight against the COVID-19, some areas or countries were locked down. Such lockdowns shut off most manufacturing operations except essential productions and caused significant disturbances to global supply chains, as enterprises in the supply chains are globally distributed across countries. The traditional supply chains are usually linear, so problems in a single link (shutdown of an area or congestion/blocking of logistics) will affect the integrity of the entire chain.

When businesses resume gradually, workforce shortages became a major issue due to travel restrictions. Some factories have to stop production due to the lack of raw materials or parts from foreign countries, while others have to slow down or shut off production because the finished products cannot be shipped abroad. Some companies also encountered difficulties with expensive equipment arrived just before the COVID-19 outbreak since the equipment manufacturers cannot send engineers to complete equipment installation and testing. There are also situations when one worker on the shop floor is infected with the virus, the entire shift of workers have to be quarantined, and the shop floor production needs to be suspended. If the function of affected shop floors cannot be replaced, the entire enterprise will be forced to stop its production due to the infection of a few employees. Panic spreading among the population distorts the usual consumption patterns and caused market anomalies. Therefore, supply chains suffer a great impact.

Similar situations can be found in almost all countries around the world. Various countries have adopted different control measures to isolate and treat infected people, call for, or force people to stay home, reduce contacts between people, in order to cut off the chain of viral infection. Therefore, it has a greater impact on work that requires more people to gather, contact, and collaborate at a close range. Many businesses in the manufacturing industry have a phenomenon of workers gathering, which will be greatly affected by the epidemic.

On the other hand, due to the different severities of the epidemic and different control measures adopted in different regions/countries, the impact on manufacturing industries is quite different. Many factories in areas with lighter epidemics and/or more effective control measures have gradually resumed to normal operations, while the activities in areas with severe epidemics may stay closed. Therefore, there is an urgent need to rethink the global factory settings and production scheduling, to improve manufacturing resilience and survivability, and to cope with the impact of unpredicted events similar to COVID-19.

We believe that collaborative intelligent manufacturing (CIM) enabling technologies, including 5G communication networks, cloud manufacturing, IoT, edge computing, big data analytics, and digital twins, can address most of the issues mentioned above. This paper tries to discuss how these technologies can help to address the challenges caused by COVID-19 and improve the resilience and viability of the manufacturing industry.

2 Resilience and viability of the manufacturing industry

CIM technologies can be leveraged to improve the resilience and viability of manufacturing enterprises at five levels: supply chain (logistics), enterprise, factory, shop floor, and equipment, as shown in Fig. 1.

New methodology: by adding alternatives at the five levels, when COVID-19 or other natural disasters break out in some areas, the alternatives in other regions can be started or used to undertake manufacturing tasks in order to fulfil the customer orders. This can ensure the resilience and viability of the manufacturing industry and reduce the impact of the epidemic on enterprise production and business. This is similar to today's emergence measures around the world: automakers turned to produce ventilators and many other small companies shifted their businesses to make masks and PPE (personal protection equipment).

Perception and interconnection: it is necessary to coordinate the management and collaboration of enterprise production activities among all the alternatives. The basis to achieve effective collaboration is pervasive perception and communication. Sensors
Fig. 1 CIM technologies to improve the resilience and viability of the manufacturing industry

or IoT devices have been widely deployed and used in the manufacturing industry, such as for monitoring and visualisation of industrial processes and logistics. New communication technologies enable more efficient and on-demand interactions among collaborative manufacturing entities. This will lay a solid foundation for collaborative scheduling models and algorithms to increase the resilience and viability of production services and supply chains. In other words, information and communication technologies (ICTs) act as the base infrastructure to catalyse the collaboration.

Collaborative scheduling: CIM technologies should integrate 5G communication, cloud manufacturing, IoT, edge computing, big data analytics, and digital twins to increase the capability of enterprises and supply chains at five levels to cope with COVID-19 [4,5]. According to manufacturing business requirements, the CIM technologies should be able to connect supply chains (logistics), enterprises, factories, shop floors and equipment to realise dynamic reconfiguration of supply chains and enterprise systems.

Alternatives, pervasive connections and collaborative scheduling can collectively realise the efficient coordination of supply chains and production activities to hedge the impact of COVID-19 or other natural disasters.

5G communication is the fifth generation technology for cellular networks, which incorporates new technologies such as SDN/VNF, millimetre-wave communication, massive MIMO, and mobile edge computing, and has the advantages of high speed, low latency, low power consumption, and massive connections. Given the impact of the COVID-19 on physical contacts, 5G allows enterprises, factories, shop floors, and machines in CIM environments to communicate with each other with high reliability and low latency in the cyberspace. 5G networks have great values in business slices such as HMIs and production IT, process automation, factory automation, logistics and warehousing, monitoring and maintenance [2].

Cloud manufacturing, as a service-oriented manufacturing paradigm, is one significant effort that has attracted wide attention [4,5]. In the cloud manufacturing model, the resources that each company in a supply chain can provide are virtualised, networked and encapsulated as cloud services. When the supply of certain raw materials for production is cut off due to the epidemic, enterprises can quickly identify alternative suppliers through the cloud manufacturing platform.

IoT can help to obtain real-time information about relevant manufacturing things for quick responses [4,6]. The IoT envisions the seamless interconnection of the physical world and cyberspace and their pervasive presence around us. Thus, the IoT can enable a greatly enhanced horizontal integration of various manufacturing resources/capabilities used in different stages of manufacturing and business-planning processes. Additionally, it can allow a vertical integration at different hierarchical system levels [4]. This provides great opportunities for existing or new manufacturing services and applications to leverage such advanced interconnections. With the help of IoT, CIM can obtain the corresponding information involved in each link and node of the supply chain in real time, which provides the basis for real-time decision-making to better resolve disruptions caused by the COVID-19.

Edge computing is a distributed computing paradigm which brings computation and data storage closer to the location where it is needed, to improve response times and save bandwidth. Edge computing extends the capabilities of computation, network connection, and storage from the cloud to the edge of the network. It enables the application of business logic between the downstream data of the cloud service and the upstream data of the Internet of Things (IoT). Therefore, edge computing provides added benefits of agility, real-time processing, and autonomy to create values for CIM in handling the impact of COVID-19 disruptions [7].

Big data analytics can help make accurate decisions. The success or failure of the IoT hinges on Big Data, which is a broad term for data sets so large or complex that traditional data-processing technologies are inadequate [4,8,9]. With the support of big data analytics, more AI algorithms can be applied to obtain insights and knowledge to cope with COVID-19. Therefore, scheduling decisions in CIM after the COVID-19 outbreak can be more accurate.

Digital twins can be defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimisation, monitoring, controlling, and improved decision making [3]. By realising profound understanding, correct reasoning and precise operation of objects in physical and logical spaces, digital twins can improve the efficiency of design operation, control and management to cope with COVID-19. Particularly, digital twin technologies can be well applied to remote installation, testing, monitoring, and maintenance of manufacturing equipment when it is difficult for engineers to be onsite.

As discussed above, CIM technologies can effectively support the real-time sensing of resources and on-demand interactions between the underlying production entities in manufacturing industries and supply chains. Facing various disruptions caused by COVID-19, a manufacturing enterprise should comprehensively consider adding redundant suppliers in its supply chain, designing strategically distributed factories, and implementing CIM technologies at all levels of its business. In the end, the company’s resilience and viability are improved, so that the company can better cope with the impact of the epidemic or other emergencies.

3 Resilience and viability of supply chains

When the area of an upstream supplier is under strict control, the company’s corresponding raw materials or parts supply may be restricted or even totally interrupted. In order to maximise the resilience and survivability of the supply chain, each company in the supply chain should cooperate with multiple suppliers [4,10], forming intertwined supply networks (ISNs), i.e. complex supply networks with dynamically changing structures, roles and behaviours of the firms involved [11]. Damages to a single link in the traditional linear supply chain can have a greater impact on the entire supply chain. Advanced ICT can provide technical supports for enhancing the resilience and survivability of ISNs [12]. In order to ensure the resilience and viability of the supply chain, the enterprise’s supply chain network should have certain redundant nodes. In production, it is necessary for an enterprise to comprehensively consider factors such as user needs, logistics, costs, and other factors to select several supply chain partners and form ISNs.

IoT and Cloud manufacturing improves the transparency of production processes and can monitor various services in production activities in real time to facilitate problem solving. With the help of the ICT, large amounts of data collected from multiple sources, including enterprise resource planning (ERP) systems, distributed manufacturing execution systems, order and logistics systems, user social networks, product lifecycle management...
systems, can be collected [13]. With big data analytics, a robust ISN can be established according to the actual situation of each supplier, logistics line status, cost, risk and other factors. Particularly, big data analytics can support the analysis of the stability of the supply chain to predict possible risks under the impact of the COVID-19.

At present, the research on the resilience and survivability of ISNs still has many limitations [11]. The introduction of technologies such as digital twins and big data analytics is expected to better assess the ability of ISNs to resist interferences (such as outbreaks) for a long time.

4 Resilience and viability of enterprises

The epidemic outbreaks and natural disasters are usually regional, and the impact of the epidemic or disasters on enterprise production usually has obvious regional effects. Therefore, a company should strategically design their multiple factories, distributed in different locations (countries, regions) when starting their business globally. When an unpredicted event like COVID-19 happens, the production tasks of an affected factory can be reallocated to unaffected factories in other regions to some extent. In such cases, when a factory suspends production activities due to unexpected situations, it will not have a high impact on the product or service supply of a company.

The establishment of multiple factories inevitably brings about transportation, coordination, collaboration and other issues, which need to be comprehensively considered before enterprise mergers and acquisitions and new factory construction. It is also very important to deploy a cloud manufacturing platform across multiple factories. The cloud platform ensures the collaboration of multiple factories in production and supply [14]. When a catastrophic scenario such as COVID-19 occurs, some factories of the enterprise may be forced to shut down. The cloud-based CIM platform obtains the corresponding information of the remaining factories and the effective nodes of the supply chain in real time, makes comprehensive decisions through big data analytics, and quickly schedules the resources in remaining factories so that the impact of the catastrophic event on enterprise production activities can be reduced.

At present, research on global distribution and management of factories in an enterprise is mostly limited to collaboration under normal operations, and there is little research on resilience and viability under disasters. The COVID-19 outbreak rises the wide attention, reflecting the necessity of redesigning factories distributed globally.

5 Resilience and viability of factories

Each factory may have multiple shop floors, which are usually distributed in an adjacent area. During the COVID-19 outbreak in China, many workers were not allowed to travel to work locations after the Chinese New Year holiday break. Then many factories faced a shortage of staff and other production resources (such as raw materials and parts). The entire production plan is disrupted, and how to ensure production is a challenge faced by enterprises.

When shop floors are initially set up in a factory, the redundancy of the shop floor should be considered, i.e. it can be replaced by another shop floor if there is a failure. With the CIM technologies, other shop floors can be quickly reconfigured to adapt to different production requirements and to ensure the overall production capacity [8, 15]. The cloud platform can support to plan the production resources of multiple shop floors in a unified manner and arrange multiple shifts. AI and machine learning, edge computing, and big data analytics can help to achieve information fusion, aid shop floors to reallocate production resources, and thus improve the resilience and viability of factories.

A cloud-edge-device computing structure [15] can be used to achieve information sharing and collaborative production between shop floors. Edge computing collects shop floor data and uploads them to the edge nodes for fast processing. Multiple shop floors interact with each other through edge computing nodes to timely exchange real-time information on the production attributes and production status. By enabling distributed computing capabilities, 5G can be used to reduce communication delays, increase interconnectivity, and potentially speed up computing tasks. A dynamic service selection method can be deployed across multiple manufacturing clouds to effectively deal with uncertainties [6]. Big data analytics can be used as a data-driven learning system, which helps to generate enough destruction scenarios and simulate coping strategies. On the other hand, the IoT enabled manufacturing system obtains real-time information on the scope and scale of COVID-19 interferences, uses digital twins technology to build multiple analysis models, and put forward a scheme to deal with interferences [16]. AI and machine learning techniques can help train interruption models and assist big data analytics in making better decisions.

6 Resilience and viability of shop floors

Under the influence of COVID-19, enterprises face supply chain breaks and logistics disruptions, which leads to an insufficient supply of raw materials and parts. As mentioned above, infected workers may also cause shop floor shutdowns and workforce shortages. The shop floor faces how to reallocate resources (including materials, parts and workers) and rearrange production activities. Factory shutdowns, supplier shortages, and workforce shortages may result in reduced production and supply chain instability.

Firstly, shop floor workers can be reassigned. As a lesson learned during the COVID-19 outbreak for many companies, it is important for workers to be trained for several jobs or positions. Otherwise, worker reassignments would be difficult, which happened in several pharmaceutical manufacturers in China recently.

Secondly, the flexible scheduling of shop floor resources can improve the resilience and viability of shop floors. The digital information technology and big data analytics in CIM environments enable shop floor scheduling more flexible and efficient [17]. Thirdly, increasing the transparency of manufacturing systems in a shop floor can improve decision-making, and increase production resilience. With the support of IoT, 5G, and digital twins, the transparency and agility of the manufacturing systems can be improved with real-time information on manufacturing objects and processes [4, 6], thereby improving the resilience and viability of shop floors.

Agent-based dynamic scheduling and control methods can significantly improve the flexibility and responsiveness of manufacturing systems [18–20]. Predictive scheduling algorithms can be used to analyse historical data on how to schedule resources to make the manufacturing system more resilient [21]. A flexible scheduling framework can be applied to optimise the manufacturing system by adjusting the processing order, system parameters, and structure [22]. The IoT realises the interconnection of all manufacturing things and systems, supports collaboration for enterprises in supply chains and increases manufacturing resilience. With the help of smart sensors and plug-and-play cyber-physical systems, the workstations in the assembly lines can change the operation processing and setting sequence according to the actual order inbound traffic and capacity utilisation [23, 24]. The software-defined cloud manufacturing system can quickly configure the production system accordingly [8, 15]. When disruptions occur, the reconfigured system implements product variants, replacing the original products to some extent, thus reducing the loss of the enterprise. In the event of serious uncertainties, manufacturing systems can even be rapidly reconfigured for new types of tasks. For example, under emergencies of the COVID-19, automobile manufacturers can quickly configure their production lines for ventilators.

Digital twins technology can be applied to simulate possible recovery strategies under the impact of COVID-19, such as changing the supply chain plan or inventory strategy to achieve output capacity [25].

7 Concluding remarks

This paper analyses the methods of applying collaborative intelligent manufacturing technologies to improve the resilience and survivability of manufacturing supply chains and enterprises to deal with unexpected catastrophic events.
fight against major disasters at five levels: supply chain, enterprise, factory, shop floor, and equipment. These methods deeply integrate emerging ICT, including cloud/edge computing, IoT, 5G, big data, digital twins, software agents, to provide manufacturing enterprises and supply chains with the ability to quickly respond to unpredicted disturbing events like the COVID-19 pandemic and ensure the resilience and viability of the manufacturing industry.

8 References

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