Chapter 10
Operations Management of Cyber-Physical Production Systems

M. A. Amrita and K. B. Akhilesh

Abstract The manufacturing industry is considered to be the backbone of majority of the economies across the globe. Over the centuries, the manufacturing industry has experienced a sea change in the various business processes associated with it. The major catalysts to these changes are predominantly due to the ever-changing customer preferences and sustainability in the era of stiff competition. Though history attributes, these changes to the change in technology but the researcher strongly believes that this change in technology and need for innovative solutions is primarily triggered due to the resource constraints, customer retention and attraction and thus instigating the need for optimisation of the resources available without compromising on the customer satisfaction and profit maximisation. The widespread adoption of computations and communications deeply embedded in and interacting with physical processes in the manufacturing industry adding new capabilities to physical systems is increasingly making the boundaries between the physical world and the virtual world indistinct and is termed as cyber-physical production systems (CPPSs). The paper aims at characterising cyber-physical systems, assessing potential benefits and challenges faced. The paper attempts to suggest some recommendations to overcome the challenges of managing operations in CPPS.

Keywords CPS · CPPS · Industry 4.0 · Manufacturing · Operations management

10.1 Introduction

The manufacturing industry is considered to be the backbone of majority of the economies across the globe. Over the centuries, the manufacturing industry has experienced a sea change in the various business processes associated with it.

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10.2 Evolution of Manufacturing Industry

10.2.1 Industry 1.0

However, taking a quick peek into the history reveals that with the advent of water and steam power which revolutionised the entire industry. The mechanical production facilities were set up by the end of the eighteenth-century keeping the first mechanical loom as the reference. This made a huge difference to the productivity of the employee as the human efforts were now supported with steam and water power. Production management during this period was more focused on standard procedures and to achieve appropriate integration between man and machine. Final inspection of the finished product was only quality initiative that was undertaken.

10.2.2 Industry 2.0

As time progressed, a bigger leap in the manufacturing industry was taken due to the discovery of electrical energy. The first assembly line was introduced which resulted in mass production, marked the advent of second industrial revolution in the history of manufacturing industry. This revolution enabled manufacturing in large volumes and instigated various changes in the work methods and workflow. Division of labour and high standardisation of products and processes were the highlights of this revolution. The focus was now shifted to extracting higher volumes from the set up which compromised on the productivity as the employees now concentrated on the volumes rather than the quality of the products. Quality was still restricted to inspection. Due to large volumes, new methods were tried and tested for the raw material procurement, order quantity decision making and inventory management. The managers tried to ensure that the defective items should not reach the customers; however, they never questioned their employees as to why the defective items were manufactured. So the beginning of the twentieth century was all about achieving economies of scale.

10.2.3 Industry 3.0

The beginning of the twentieth century witnessed yet another substantial change which took the manufacturing industry by storm. The third industrial revolution was characterised with high application of electronics and information technology which automated the production system. Computer controlled and computer enabled systems were used for production which further reduced human efforts. Managing operations in these kinds of plants gained a new meaning as the human intervention was now concentrating more on reducing defects rather than identifying defects in the final product. Improved transportation facilities prompted the companies to cater to newer markets beyond their geographical periphery. This gave rise to intense competition invariably putting pressure on the manufacturing industries to optimise at all levels without compromising on the requirements of the customers. Operations management underwent a paradigm change from simple Quality control to Quality Assurance to Quality Management finally leading to a holistic philosophy of total quality management. The focus was now not only on production processes but on all the support processes which enabled smooth manufacturing of the products. Factories were now aiming to get leaner and improve continuously.

10.2.4 Industry 4.0

Despite all efforts, the factories still faced many challenges due to human errors and rapidly changing customer preferences mostly attributed to easy access to the global information via Internet. Companies now not only have to produce as per ever-changing customer demands but should simultaneously demonstrate agility at all levels. Though the practices and production systems were IT enabled, they functioned as independent sub-systems. The industry felt the need to have seamless integration between these systems and with the outside world as well. The outcome of this need marked the beginning of the fourth industrial revolution. Germany is considered to be the pioneer of this revolution.

10.3 Cyber-Physical Production Systems (CPPS)

10.3.1 Understanding CPPS

The widespread adoption of computations and communications deeply embedded in and interacting with physical processes in the manufacturing industry adding new capabilities to physical systems are increasingly making the boundaries between the physical world and the virtual world indistinct and are termed as cyber-physical production systems (CPPSs) (McKinsey & Company 2017).

CPPSs are networks of machines that are arranged to behave like social networks. In simple words, they integrate mechanical and electronic components with information technology. The communication between each component is enabled through a network. One of the earlier examples of this integration is radio frequency identification (RFID) technology, which was operational from 1999.[1]

The major difference between the traditional production system and CPPS is that it continually shares information about current stock levels, problems or faults, and changes in orders or demand levels and is capable of adapting to newer product design with ease and carries out self-maintenance. This information sharing between the machines and the systems helps to coordinate the processes to meet the scheduled delivery date and in turn aims at boosting efficiency, optimising throughput times, capacity utilisation and improved quality in product development, production, marketing and procurement.

CPPSs not only aim to link machines with each other, they also create a smart network of machines, properties, ICT systems and smart products. It aims to link together vendors, employees and customer in the real-time scenario across the entire value chain and the full product life cycle. CPPS is largely dependent on sensors and control elements which enable machines to be linked to plants, fleets, networks and human beings. This integration is called as the Internet of things (IoT) which can be further extended to Internet of things, services and human beings.

The Industry 4.0 amalgamates 3D printing, sensor technology, artificial intelligence, robotics, drone and nanotechnology that are dramatically changing industrial processes and making them responsive in real time which aids them to be agile and human error-free to an extent. The researchers are anticipating an exponential growth in the industry due to the advent of CPPSs.

10.3.2 Characteristics of CPPS

CPPSs are characterised by:

1. Intelligent Information acquisition system
2. Ability to connect and communicate between system elements
3. Real-time responsiveness to internal and external changes.

10.3.3 Digitally Integrated and Intelligent Value Chain—Limitless Possibilities

- **Substantial gains in the productivity**: According to the research conducted by Boston Consulting Group (2015) adoption of Industry 4.0 will lead to an increase

[1]Industry 4.0, Challenges and solutions for the digital transformation and use of exponential technologies, Deloitte.

in productivity by 4–7%. Integrated manufacturing and logistics processes are attained by complete vertical (internal) and horizontal (supplier, customers) data integration resulting in real-time and smooth reaction of manufacturing systems to changes in the production process. Set up time and cost can be reduced by flexible small-batch manufacturing which is completely automated. Fully automated logistics and consignment systems result in reduction of failures as well as in consignment lead time, thereby positively impacting the productivity and satisfaction levels of the customers.

- **Significantly higher levels of automation**: There have been evidences of usage of robots in the manufacturing industries in the past. Earlier robots were designed to deal with complex assignments; however, at present, robots are developed to become autonomous, flexible and cooperative by using artificial intelligence. Eventually, they will interact with one another and work safely even when placed adjacent of the humans and learn from them. The high demand and advanced technologies are drastically lowering the cost of these robots but will be possessing increased capabilities than the current ones (KPMG 2016).
- **Drastic improvements in resource efficiency and effective asset utilisation**: Human resources, material resources and energy are considered to be the most important inputs to any manufacturing industry. The sole aim of any factory is to optimise all the resources leading to better utilisation of monetary resources and also demonstrate sustainability in the long run. The seamless integration of man and machine reduces wastage of any human effort and thereby channelising their energies and competencies towards more value-added work. Standardisation of processes and robust product design act as an input to the intelligent systems, which are programmed to appropriately handle the material on the shop floor and also simultaneously update the status of the inventory, thus reducing wastage due to overproduction, over ordering and inappropriate material handling. Intelligent systems monitor the apt use of energy by using it only when required, thus automatically saving on the wastage of the energy. Apart from this there is an integration of smart components with low-energy consumption which further improves the resource efficiency. According to research by McKinsey & Company, PWC and Roland Berger, energy management using IoT can reduce factory energy costs by 10–30%. The human–robot symbiosis optimises the plant layout and has a positive influence on utilisation of the assets of the organisation both in terms of space as well as workflow sequence and dynamic scheduling. The focus is not only on improving the resource efficiency but also on the creating environmental sustainability.
- **Self-X—Self-organisation, self-maintenance, self-repair**: In CPPSs, workflow is sequential and continuous in nature and all the systems are interlinked with each other, break down at one particular junction can disrupt the working of the entire process irrespective of the production systems, e.g. job shop, intermittent, assembly line or continuous production system, which can have adverse effect on the entire organisation. Thus intelligent systems are very essential part of this set up as they are trained and programmed to detect faults and self correct them. This intelligence should go one step beyond by not only detecting faults but also anticipating one and

thereby taking proactive actions. Based on the research conducted by McKinsey & Company, predictive maintenance using IoT can minimise maintenance costs of the equipments by 10–40% and diminish the equipment downtime by up to 50%. The additive manufacturing which is capable of 3D printing the products has a humungous amount of influence in taking self-maintenance to newer levels. Use of additive manufacturing can be used to make customised spare parts in variety of materials to effect immediate repair thus further reducing the downtime.

- **Remote and real-time diagnosis and control**: IoT is breaking the geographical barriers and organisations are borderless. The main highlight of Industry 4.0 is that it demonstrates agility in all aspects especially while responding to customer's issues. These customers can be both internal and external, real-time identification of problem areas and effective and real-time solutions to the problems faced is the need of the hour for better operational efficiency and market sustenance irrespective of the geographical location. Due to IoT, remote and real-time diagnosis and control can be carried out with ease.
- **Better product quality**: With reduced product life cycles and demand for innovative products, manufacturing a good quality product is challenging. However, with seamless integration of the production systems, vendors and customers, real-time feedback can be obtained and due action can be taken up to resolve customer issues. Vendors can also contribute to the proposed solution, thus taking the product quality to newer heights. With the advent of 3D printing technology, one-to-one customisation is now achievable with lesser complexity.

10.3.4 Digitally Integrated and Intelligent Value Chain—Challenges

In the present scenario, the researchers are projecting the CPPSs as very promising systems; however, these systems are still in their nascent stage and require incubation. Organisations are facing many challenges to meet the high expectations of this intelligent system. These challenges include but are not limited to:

- **Lack of customised decision support systems to manage complex systems**: The CPPSs are completely data-driven. Big data analytics is one of the prime drivers of almost all the business processes. Though there are intelligent sensors collecting data in real time. Managing, storing, retrieval and effective utilisation of this big data is complex. Apart from this, identifying the process parameters for data collection is critical and requires very deep understanding of the process and its impact on the entire business. Design and development of good decision support systems will enable the organisations to improve the quality of the data and leverage on the analytics provided by them. However, designing and further developing a robust decision system are tough as the collaborative partners need to have sound technical knowledge of the end-to-end process, in-depth understanding of process variable along with the computational and communication aptitude.

- **Lack of interoperability**: There are multiple users in the same virtual value chain with different technologies who are continuously collecting, sharing and analysing the information across the globe. The availability of numerous technologies and platforms add to the complexity of effective and convenient collection and dissemination of information due to which there is possibility of losing important information which could prove to be expensive in the long run. If the partners decide or dictate use a particular technology and standard form of data sharing, non-value adding investments are triggered since each partner will emphasise on a particular technology.
- **Lack of cybersecurity systems and regulatory frameworks**: The digital value chain within the smart factory is prone to cyber threats if they continue to use traditional IT security tools. With new advancements in the IoT-based products, processes and general operations, the companies are becoming increasingly vulnerable to cyber attacks. Organisations should make concentrated efforts to identify and fathom the risks associated with the digital value chain. The impact of these threats proves to be very expensive for the factory.
- **Inadequacy of broadband infrastructure**: With smart factories, smart products and smart materials, the ubiquitous presence of Internet and sensors are very essential. The presence should further be strengthened with adequate speed. Absence of Internet with adequate speed and the infrastructure ability to collect, store and analyse can result in disruption of manufacturing activities and may also lead to loss of historical data which can prove to be detrimental for effective operations management.
- **Safety issues**: The robots and the humans work in closer vicinity in an industrial IoT set-up. Lack of synchronisation between the two can lead to safety issues. Though robots are now enhanced by artificial intelligence and neural networks, developing a high degree of human-machine symbiosis is a task which requires concentrated focus. The human in turn exhibits initial inhibitions to synchronise and synergise with the machines due to the overpowering and overwhelming use of the technology which leads to operational hazards and accidents.

10.4 Overcoming Challenges

Although there are many challenges faced by the manufacturing industries to achieve seamless integration, industry cannot ignore the benefits associated with CPPSs. The following proposed strategies aim at effective operations management, their feasibility is yet to be tested.

Suggestions to overcome challenges—

- Start to end ***workflow mapping*** with complete details ranging from cycle time at every machine, activity undertaken, details of process parameters, related variables and collection points along with a list of all possible analysis and the corresponding end-users of the analytical output. This detailed workflow map will enable to

develop customised decision support system which will be equipped to handle complex systems with ease.

- **Interoperability** can be established by transitioning from reference architecture to standardised system based on revised regulatory framework. The standardisation will result in '***plug and work***' level of user-friendliness.
- Cybersecurity risks can be mitigated by robust and ***agile cybersecurity systems and reframing of cyber laws and regulatory framework*** pertinent to cover all possible infiltration and aid in cyber risk recovery. Industrial IoT devices must be highly secure by design, and securely integrated into existing automation and information system architectures. The industries should come together to build high level of resilience within the processes and equipments of the company. As the breaches cannot be totally avoided, appropriate detection and response mechanisms are required to be developed to overcome these threats. Resilient factories can seek competitive edge over others by providing greater assurance to their customer and all the stakeholders.
  - Adequacy of ***Broadband infrastructure*** can be attained by using above-mentioned workflow map in conjunction with appropriate forecasting techniques to estimate the quantum of data to be handled at present and in future. Based on this, estimation specifications of adequate and robust broadband infrastructure can be identified.
  - The ***e-Poka Yoke*** can be built in the systems which will guide the humans and refrain them from committing any form of error. For example, sensors can be installed on the shop floor area designating every employee's work zone, stepping out of the work zone while performing the activity will halt the system thereby avoiding any form of collision with the accompanying robots and it automatically resumes the work as soon as the employee steps in. To strengthen the ***human-machine symbiosis***, integration of a geometric data framework with fusion assembly features and sensor measurements is essential. Fast search algorithms to adapt and compensate dynamic changes in the real environment furthers the process. ***Capability building programs*** should be conducted at various levels including all the actors from upstream value chain to downstream value chain and develop user-friendly apps for customers for effective applicability despite their age and qualification.
- To aid better operations management ***Visual Asset Management*** is essential. The wireless interconnectivity between the systems poses difficulty in obtaining a complete picture of the entire production process in one frame. This complete picture provides better understanding of the processes assisting in better management. It also helps to identify problem areas instantly. Taking the above workflow map as a reference, a dashboard with critical process parameters can be created. **Augmented reality** can be used to enhance the visual impact and obtain better visibility of the work stations. The dashboard will give the real-time status of the orders, inventory, processes and dispatched consignment simultaneously alert whenever there is a deviation from the plan.

10.5 Conclusion

Industry 4.0 has disrupted the traditional manufacturing processes as well as business models. The future belongs to CPPSs with its unique ability to help manufacturing organisations attain high levels of optimisation where some of the industries are reaping the benefits whereas many of the businesses are trying to upgrade themselves digitally. Operations management plays a very key role in impacting the organisations' performance by triangulating product, process and technology. CPPSs empower the organisation to add value to their businesses.

10.6 Future Trends in CPPS

The major objective of the operations management is to reduce wastages and subsequently add value to the entire process, resulting in optimisation of resources, eventually leading to profit and value maximisation. The future trends discussed are anticipated to further leverage on the benefits of CPPSs. Usage of **Social Manufacturing Systems** similar to present social networks to horizontally integrate the suppliers, employees, service providers and customers. **Customer enabled manufacturing** directs the production system to manufacture product based on the specifications selected by the customer virtually Transition to **Cybernetics** systems which are end to end self-managed systems or auto-guided systems.

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