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Smart manufacturing

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Manufacturing has evolved and become more automated, computerised and complex. In this paper, the origin, current status and the future developments in manufacturing are disused. Smart manufacturing is an emerging form of production integrating manufacturing assets of today and tomorrow with sensors, computing platforms, communication technology, control, simulation, data intensive modelling and predictive engineering. It utilises the concepts of cyber-physical systems spearheaded by the internet of things, cloud computing, service-oriented computing, artificial intelligence and data science. Once implemented, these concepts and technologies would make smart manufacturing the hallmark of the next industrial revolution. The essence of smart manufacturing is captured in six pillars, manufacturing technology and processes, materials, data, predictive engineering, sustainability and resource sharing and networking. Material handling and supply chains have been an integral part of manufacturing. The anticipated developments in material handling and transportation and their integration with manufacturing driven by sustainability, shared services and service quality and are outlined. The future trends in smart manufacturing are captured in ten conjectures ranging from manufacturing digitisation and material-product-process phenomenon to enterprise dichotomy and standardisation.

Keywords: smart manufacturing; data mining; automated manufacturing systems; design of production systems; sustainable manufacturing; product life cycle; intelligent manufacturing systems; transportation; cyber-physical systems

1. Introduction

One of the widely used terms describing the production of tomorrow is smart manufacturing. The volume of publications on smart manufacturing is rapidly growing. Many publications focus on in-depth coverage of the topics shaping smart manufacturing. This paper defines what the author believes are core concepts of importance to smart manufacturing in the hope of streamlining and systemising the growing body of research.

Smart manufacturing has attracted attention of numerous researchers who reported their findings in the literature. Thoben, Wiesner, and Wuest (2017) discussed the main characteristics of cyber-physical systems and provided an overview of Germany's Industry 4.0 initiative and manufacturing efforts undertaken in other counties. An attempt was made to identify relevant research issues. Kang et al. (2016) reviewed the literature related to smart manufacturing and identified technologies of importance to its progress. In addition, some future trends in smart manufacturing were discussed. Helu et al. (2016) defined requirements for data-driven decision-making in manufacturing. Based on these requirements, main technologies and barriers facing implementation of data-driven decision-making in industry were identified. Lu, Morris, and Frechette (2016) reported on the standards that may impact products, systems and business aspects of smart manufacturing. O'Donovan, Bruton, and O'Sullivan (2016) focused on problems facing applications of data analytics in industry. The authors advocated the use of formal methodologies to develop analytics capability rather than focusing on prescriptive approaches. The methodology discussed in their paper was demonstrated with a case study. Standards are important in integration of smart manufacturing technologies facing transformation challenges, some of which were outlined in Macke, Rulhoff, and Stjepandic (2016). A tool deployed on mobile devices for initiating queries in support of incoming changes was discussed. Zhang et al. (2014) overviewed technologies such as cloud computing, internet of things, service-oriented solutions and high performance computing. It was suggested that they make a cloud manufacturing platform outlined in their paper. Shafiq et al. (2015) proposed a framework for knowledge representation of engineering objects incorporating relevant knowledge and experience. It was demonstrated that the framework was a specialisation of a cyber-physical system. Zhong et al. (2017) discussed the concept of smart manufacturing objects handled with the internet of things and wireless technologies. Data analytics was applied to study behaviour of smart manufacturing objects.

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Besides architectures and concepts of interests to smart manufacturing, research offering specific models and algorithms has been initiated. Ivanov et al. (2016) addressed the short-term supply chain scheduling in a smart factory. A scheduling approach involving non-stationary jobs flow and temporal decomposition was developed. Moon and Park (2014) offered a scheduling solution for management of energy consumption in manufacturing. Chun and Bidanda (2013) reviewed the literature on sustainable manufacturing. They raised the issue of sustainability in global manufacturing, design for sustainability, product life-cycle management and green supply chain management.

Cybersecurity is paramount to the progress in smart manufacturing. Kim and Chang (2014) discussed information leakage vulnerabilities faced by organisations and offered some solutions.

2. The roots of smart manufacturing

The modern era manufacturing has its roots in the past half century. The progress in computer and machine-building technology has led to automation in manufacturing. Today's machine tools are largely run by computer programmes rather than human operators. Materials and components are transported by automated material handling systems and stored in automated storage and retrieval systems. Depending on the scope and degree of automation of a manufacturing floor and the integration of various functional production areas, different terms have been used to describe automated manufacturing since 1980s, ranging from flexible manufacturing cells and flexible manufacturing systems to computer-integrated manufacturing and intelligent manufacturing. The last term was coined around 1990 and marked with the establishment of the Journal of Intelligent Manufacturing (Kusiak 1990a) and publication of the book, Intelligent Manufacturing Systems (Kusiak 1990b) both under development for years prior to appearing in print. At about the same time Japan has embarked on research in intelligent manufacturing that has led to the establishment of the Intelligent Manufacturing System (IMS) Programme in support of industrial research in 1995. It was realised that the industry of one country alone could not reshape manufacturing and that international cooperation was needed. Major companies from Japan, United States, Korea and European counties have initiated collaborative efforts on the future of manufacturing, with Japan having the largest number of actively involved corporations. In the United States, much of the IMS activities have taken place under the umbrella of the Next Generation Manufacturing Systems (NGMS) Programme that was established as a not-for-profit venture. Later, the IMS Programme was expanded, with the European Union establishing research efforts in intelligent manufacturing (see Groumpos 1995).

Manufacturing is evolving, and it is bound to take place in different forms. In recent years, the concept of internet of things has attracted attention of the manufacturing community. It focuses on integration of the physical assets of manufacturing with the cyberspace to form cyber-physical systems. This new concept has been embraced by individual companies, industrial consortia, regions and countries.

There is no generally accepted definition of smart manufacturing. According to the National Institute of Standards and Technology (NIST) smart manufacturing is fully integrated, collaborative manufacturing system that respond in real time to meet changing demands and conditions in the factory, in the supply network and in customer needs.

Smart manufacturing integrates manufacturing assets of today and tomorrow with sensors, computing platforms, communication technology, data intensive modelling, control, simulation and predictive engineering. Smart manufacturing utilises the concepts of the cyber-physical systems, internet of things (and everything), cloud computing, service-oriented computing, artificial intelligence and data science. Once implemented, these overlapping concepts and technologies will make manufacturing the hallmark of the next industrial revolution.

A general concept of a smart manufacturing enterprise is illustrated in Figure 1.

The concept in Figure 1 includes two basic layers, the manufacturing equipment layer and the cyber layer, linked by the interface. The manufacturing equipment has its own intelligence, while the system-wide intelligence is provided by the cyber layer.

Smart manufacturing has attracted attention of industry, government organisations and academia. Various consortia and discussion groups have been formed to develop architectures, roadmaps, standards and research agenda. The general concept of smart manufacturing system in Figure 1 needs to be translated in architectures that are quite specific. Efforts are under way to develop such architectures. The general concept in Figure 1 is intended to support the ideas presented in this paper rather than offering a new enterprise architecture.

3. Pillars of smart manufacturing

Smart manufacturing has been inspired by the concepts largely developed in the realm of computing. Though manufacturing will continue benefit from these concepts and other ideas that will emerge (e.g. quantum computing could be a major disruptor), it has its own identity captured in six pillars that are discussed next (see Figure 2). They are neither

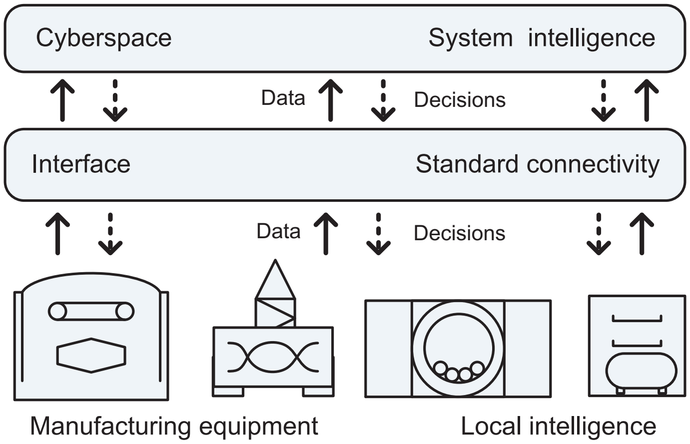

Figure 1. General concept of a smart manufacturing enterprise.

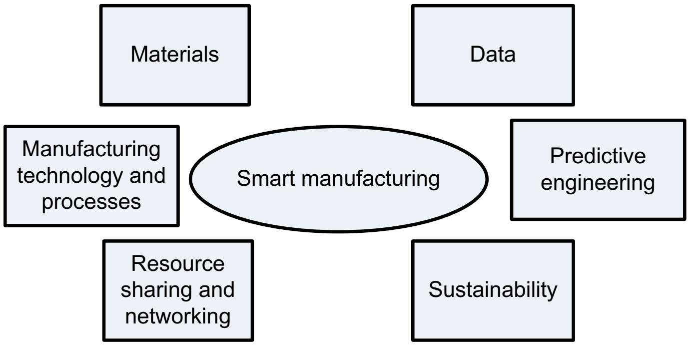

Figure 2. Six pillars of smart manufacturing.

exhaustive nor stationary. The ultimate pillars will be defined by the research, technology development and applications that will emerge in the future. The ultimate pillars could be formally defined in number of ways, including clustering of the research papers, industrial reports and information about new technology with text and data mining algorithms.

The six pillars of smart manufacturing are manufacturing technology and processes, materials, data, predictive engineering, sustainability and resource sharing and networking. The names and the degree of importance of these six pillars have been changing, however, they have been around manufacturing throughout its history. For example, data has been an integral part of manufacturing. In the era of smart manufacturing it has become big data. Production planning and forecasting have preceded predictive engineering versed in data science of today.

Details of the six pillars of smart manufacturing are discussed next.

***Pillar* 1: Manufacturing technology and processes**

The emergence of manufacturing technologies and processes are expected in future years. New materials, components and products will emerge (Kusiak 2016a). Additive manufacturing can serve as an example of a new technology that has prompted the development of new materials, impacted the design and manufacture of products and opened doors to new applications such as biomanufacturing. Manufacturing tools have been designed to integrate various operations, e.g. machines that are capable of horizontal and vertical milling as well as drilling (a machining centre). New hybrid processes will emerge, e.g. hybrids of traditional and additive processes, laser and net-shape manufacturing. Greater integration of processes will occur, e.g. integration of new materials, product design, manufacturing processes, such as discovery of a chemical compound leading to design of a new medication and a delivery device, as well as the manufacture of medication and the device. Big and small area additive manufacturing will expand its prominence in the factories. New generation of low cost robots will enhance factory automation. Sensors and software capabilities will make the new manufacturing equipment smarter and amenable to factory and beyond communication.

***Pillar* 2: Materials**

Smart manufacturing does not make a special call for the development of smart materials, e.g. shape memory alloys or functionally graded materials. It may well be that smart materials and smart products will follow their own development paths. Smart manufacturing is open to all types of materials, including organic-based materials and biomaterials, needed to produce future products. The significance of recovering materials from products at the end of their lifecycle will increase. It is conceivable that landfills will become new mines of various materials. Some new materials will require novel processes that must be developed and incorporated in smart manufacturing. Additive manufacturing alone will be a great contributor to the search for new materials and their mixes.

***Pillar* 3: Data**

We are witnessing the renaissance of data in manufacturing. Some of it has been triggered by deployment of sensors, wireless technology and the progress in data analytics. Greater collection of data from diverse sources, ranging from material properties and process parameters to customers and suppliers has begun. The data will be used to power any application to be envisioned, including building predictive models. Moreover, it will be the best source for preserving and extraction of past and new knowledge related to manufacturing.

***Pillar* 4: Predictive engineering**

Predictive engineering is one of the latest additions to the space of manufacturing solutions that will lead to an anticipatory rather than reactive enterprise. Traditionally, the manufacturing industry has focused on using data for analysis, monitoring and control, e.g. productivity analysis, process monitoring and quality control. Six sigma and other data-analysis concepts have had tremendous impact on advances in the quality of manufactured products and services. However, for the most part, traditional efforts have emphasised the past over the future states of manufacturing processes and systems. Predictive engineering offers a new paradigm of constructing high-fidelity models (digital representations) of the phenomena of interest. Such models will allow exploring future spaces, some within the realm of the existing technology and others that have not been seen previously. In the future, today's models will be enriched with both limited-scope models (e.g. behaviour of a supply chain) and those that involve multiple systems (e.g. models that integrate productivity, product quality, energy and transport) to support decisions concerning future production and market conditions. Such wide-scope models may contribute to restructuring the manufacturing industry. It is conceivable that some manufacturing will become highly distributed and some may be centralised. For example, products that are sensitive to the transportation cost, time-to-market and customisation could be produced at locations in the proximity to the customers.

***Pillar* 5: Sustainability**

Sustainability will be of paramount importance in manufacturing. The goals of sustainability efforts will be materials, manufacturing processes, energy and pollutants attributed to manufacturing. The entry points of any major sustainability effort are the product and the market. There is no doubt that the greatest sustainability gains are accomplished when the development of products and processes is guided by the sustainability criteria. Examples of possible scenarios include: (i) sustainable product design will drive manufacturing, (ii) sustainable manufacturing processes will impact the design of products and (iii) simultaneous development of sustainable materials, products and processes will take place. Additive manufacturing represents the second scenario in which a process has resulted in new designs of components and products.

Sustainability is not about what is manufactured but how it is performed. It is the main force behind providing equal footing for remanufacturing, reconditioning and reuse with manufacturing. Because of sustainability, the line between manufacturing and service will remain blurry. For example, reconditioning a used product is not a traditional manufacturing activity, however, it may enter the new manufacturing dictionary.

***Pillar* 6: Resource sharing and networking**

As manufacturing is becoming digital and virtual, much of the creative and decision-making activities will take place in the digital space. While at some level the digital space may be highly transparent, the physical manufacturing assets with their know-how will be protected. This digital-physical separation will allow for shared use of resources across businesses, including the ones that compete.

The manufacturing industry has been exposed to service and contract models with production taking place at facilities operated by a third party. The rapid manufacturing (a predecessor of 3D printing) service model was established decades ago as a result of the high cost of technology, low utilisation, learning curve and uncertainly about utility of the technology. Shared resource models have seen success and are expanding from sharing rides aimed at reducing highway traffic to Uber in transportation and Airbnb in accommodation services. Smart manufacturing is likely to benefit from these concepts to share manufacturing equipment, software, expertise and most importantly, the collaborative modelling and creativity space (Kusiak 2017b).

While the logistics of leasing manufacturing equipment and sharing commercial software could follow the existing models, sharing the creativity space is a challenge. Application of the principles similar to those of Facebook and

Wikipedia to various areas of manufacturing is not easy and will likely take decades to realise. All sharing transactions will be accomplished in the space populated with digital models rather than physical assets.

Besides the manufacturing equipment, transport is a meaningful resource that deserves attention. There are two broad categories of transport in manufacturing: internal, involving specialised material handling equipment or various tracks and external, which serves the supply and distribution chain. From the manufacturing accounting point of view, transport is generally considered as a non-value-adding activity. This triggers a thought that minimising the distances travelled would not only reduce the cost, but also have a positive environmental impact. Developments in robotics and autonomous vehicles (from surface to air) will impact the internal and external manufacturing transport by increasing its degree of autonomy and sharing. Transport will be an important factor in evolving the spatial configuration of manufacturing on a regional and global scale.

3.1 *Beyond the manufacturing tradition*

The manufacturing of the future will naturally expand into non-traditional areas such as:

- Healthcare largely driven by the need to customise products, from the implants and medications to the hospital and home care supplies;
- Biomanufacturing fueled by the promise of tissue and organ printing.

Both small area additive manufacturing (e.g. surgical equipment) and large area additive manufacturing (e.g. hospital beds, furniture) will be the key drivers in the healthcare industry.

In addition, the domains that might have been considered as marginal will gain more prominence, e.g.:

- Remanufacturing and reconditioning are bounded to grow especially when novel design practices will be deployed;
- Disassembly and reuse will become growing contributors to the circular economy.

Sustainability, increasing cost of traditional materials and limited availability of traditional materials (e.g. rare metals) will support the circular economy.

4. Material handling and transport of materials, components, products and people

Material handling and transport are inherent functional areas of manufacturing involving distances measured in nanometer to kilometre scale. Both support manufacturing processes and shipment across different plants and around the globe. While material handing is usually used to describe the movement of material in a factory, transport is associated the movement of materials, components and products through supply chains covering regions, counties and continents (see Figure 3). Material handling and transportation can be significant contributors to the product cost, e.g. 8% of the cost of a wind turbine tower is attributed to the transport (Cotrell et al. 2014) and higher percentage (e.g. 20%) to other components.

It is likely that due to the distributed nature of manufacturing, transport of materials, components, products and people will become a significant cost item in production. This will naturally lead to optimisation of the transportation and utilisation cost of personnel supporting the physical and digital infrastructure at multiple manufacturing facilities. Job description that do not exist today, will be created to meet the smart manufacturing tasks. Similar to components,

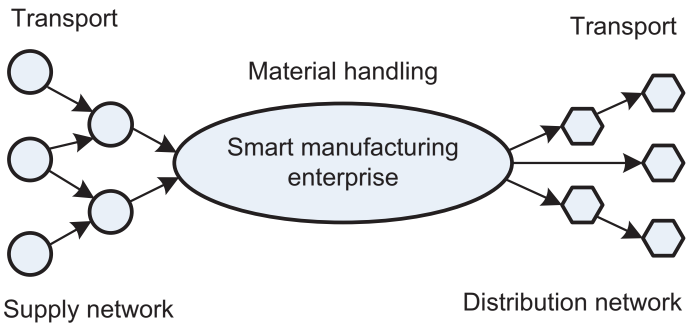

Figure 3. Integration of manufacturing with supply and distribution chain.

e.g. differentiating the products, manufacturing specialists could be travelling in large numbers using different modes of transportation from cars to trains and plains. As discussed later in this paper, analogous to the manufacturing resources, human resources are likely to be shared in large numbers. The efficiency of transporting materials, components, products and people will impact the manufacturing cost. Transportation and communication are the cornerstone of global connectivity in manufacturing. Irrespective of the ownership, transportation is likely to become an integral part of smart manufacturing due to: (i) greater reliance on the movement of materials, components, products and service personnel driven by personalised needs, (ii) sustainability; (iii) quality of service. Transportation networks involving the supply side and distribution (including customer delivery) similar to the one shown in Figure 3 are likely to play a meaningful role. Limiting the sustainability consideration to the manufacturing envelope, would provide a suboptimal solution due to interconnectivity of manufacturing with the supply and distribution network trade-offs. The quality of customer service is tightly connected to the inventory level, manufacturing response time and transportation.

4.1 *Smart vehicles*

Many material handling and transportation vehicles operating today send and receive data. The vehicle connectivity will become more intense, with greater participation in the information exchange, e.g. vehicle-to-vehicle communication or vehicle-to-maintenance centre for remote diagnostic and repair. In fact, machine tools are likely to follow the same path of communications supporting condition monitoring and production.

The vehicle technology circle in Figure 4 classifies transportation vehicles based on the vehicle/fuel type and vehicle automation/use. Vehicles based on any combination of the vehicle/fuel type and vehicle automation/use attribute are captured. For example, it is obvious that a vehicle can be autonomous and electric. This applies to material handling systems, personal cars, trucks and mass transit. It appears that the technology is naturally gravitating towards linking the notion of transportation, energy and sustainability with manufacturing. Vehicle of any type, e.g. a forklift, a car, a truck or a long-distance train, can be electric and autonomous. In addition, vehicles could be shared.

To date, the batteries of electric vehicles are charged by electricity that is usually generated by traditional power plants. In the future, vehicles will use electricity generated from renewable sources, e.g. wind turbine-produced electricity or hydrogen, and they will be designed for sustainability, including energy efficiency. An energy-efficient vehicle will use less material and its geometry will be shaped to reduce aerodynamic drag. At the end of its life, most of its components will be reused and remanufactured. To date, the subject of the sustainable design of electric vehicles has received limited attention. Perhaps the vehicle industry is overly preoccupied with making a successful entry in the autonomous market.

This concept of vehicle connectivity is not new. It has existed in the domain of public transportation for a long time. In the mass-transit domain, it was implemented in two forms, i.e. the physical and information connectivity. A train is a physically connected vehicle with over-the-wire or wireless communication. The benefits of the traditional connectivity may apply to the new generation of vehicles and material handling solutions. Similar to machine tools, vehicles can be connected physically or virtually. The virtual connection can be accomplished in several ways, ranging from the vehicle-to-vehicle communication to the traffic control level. A connected vehicle is a natural result of the evolution in productivity, efficiency and safety of transportation. For example, similar to manufacturing where one operator may operate multiple machines, having one driver per many vehicles offers a cost advantage.

The idea of shared transportation in the personal-vehicle domain has existed for years. The reward for shared transportation usually was in the form of access to a less-congested lane on the highway. The owner of the vehicle generally

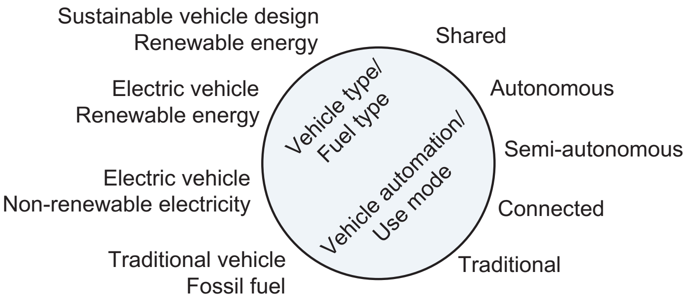

Figure 4. Vehicle classification based on vehicle/fuel type and vehicle automation/use.

is one of the passengers. Shared group transportation is a well-established practice, ranging from small groups (e.g. six to ten people in a van) to a mass transit system.

Using a vehicle that we own for personal transportation is inefficient from the standpoint of energy and cost. The utilisation of personal vehicles is usually low. We tend not to think that way, however, when what we really need is a transportation service, without necessarily owning a vehicle. Subscribing to the transportation service concept offers increased utilisation of vehicles and reduces transportation costs. The increased utilisation, in turn, reduces the number of vehicles on the roads, thus having a positive impact on the traffic congestion and environment.

We are not that far from being on the top of the vehicle technology circle in Figure 4. The capacity of the batteries is expanding. At present it is sufficient for most trips driven. All major manufacturing companies, including Ford, BMW and Volvo, promise to deliver driverless cars (in some cases without a steering wheel and pedals) in the next few years. Irrespectively of the level of autonomy, a future vehicle will be more automated, connected, energy efficient and safer to drive. He hope is that electricity generated from renewable sources will power the vehicles and factories. The factories will use renewable materials to manufacture components that meet the transportation needs.

There is no magic switch and time for changeover from the transport of today to the autonomous one. Neither there is no clearly articulated goal for the level of autonomy. As with any new technology the transport autonomy will follow a process beginning with some niche implementations and gradually expanding to most suitable domains, e.g. manufacturing supply and distribution chains.

The missing link that prevents connecting the dots between autonomous, personal, shared and sustainable transportation is the human factors, rather than technology. In the vehicle-sharing mode, the difference between the personal and the mass-transportation modes may not be clear. Clearly, transportation is more economical when the materials and passenger loads and grouped, e.g. two connected trucks, rather than multiple vehicles with limited load in each vehicle.

Besides being autonomous, vehicles are becoming more reliable. Predictive engineering solutions will anticipate future events, ranging from a component of the vehicle that may need repair to a potential accident. The on-board decision system will offer the best options to proceed in order to avoid a component failure or an accident impacting the delivery time. All disruptions will be communicated to the manufacturing facilities that might be affected by the transport.

Different forms and modes of transportation will be used to support the supply and distribution chains of manufacturing. A shared mode of transportation is likely to be applied to move experts servicing the manufacturing systems, as well as materials, parts and products.

5. The future of smart manufacturing

Smart manufacturing offers opportunities and challenges. The greatest challenge could be in the acceptance of the emerging manufacturing reality and change. A new wave of factory automation will be supported by the next generation of low-cost robotics. This alone will create new 'cyber' jobs rather than traditional jobs. The conversion of blue-collar jobs into white-collar jobs is not new, yet it is a challenge every time it happens. The 'cyber' part of the smart factory, in itself, is an enterprise within the enterprise, with jobs descriptions to be defined and a workforce to be trained by the educational establishments. The better we understand the future needs, the better smart enterprise will function.

The transformation of the manufacture of today to the manufacture of the future is an enormous task. No single corporation can be effective in accomplishing all tasks on its own due to the market and technology uncertainty. The items actions needed for smart manufacturing to be successful are outlined in Kusiak (2017b).

Smart manufacturing is evolving and its specifics will emerge in years to come. Some of the characteristics of the future manufacturing are captured by the ten conjectures outlined next. For each conjecture a brief justification of provided. The conjectures are intended to capture the essence of smart manufacturing. Some of them may become validated or become less prominent of even discarded over time, while new conjectures may be formed. They may enhance understanding of the core manufacturing issues as well as capture trends and changes affecting smart manufacturing.

***Conjecture* 1: Manufacturing digitalisation**

Manufacturing will be increasingly dependent on data which implies than more data needs to be collected.

Justification: The increased use of data is already happening in many manufacturing sectors. One of the practices manufacturing could benefit from is that of wind energy industry where supervisory control and data acquisition (SCADA) systems have been used (Kusiak 2016b) to store large volumes of data on process parameters. SCADA solutions offer a convenient way of capturing, storing and sharing process data.

***Conjecture* 2: Increased reliance on modelling, optimisation and simulation**

The growing volume of data (Conjecture 1) in smart manufacturing will naturally open doors to delivery of value from the data.

Justification: Data-driven modelling approaches will gain prominence as they allow to integrate parameters across different domains (e.g. product, process and logistics) into models that would be difficult to build with traditional methodologies (e.g. mathematical programming). Dynamic predictive models will be frequent occurrences in smart manufacturing. Virtual, augmented reality and predictive models will become routine constructs.

***Conjecture* 3: Material-product-process phenomenon**

The number of instances with the new material, process and product developed simultaneously will grow.

Justification: Some of the past innovations have taken place when a new material and a process had been created at the same time. In is likely that in the future the development of materials, processes and products will lead to innovations, e.g. design of a 3D printed part will be optimised in conjunction with a new material and a process.

***Conjecture* 4: Vertical separability of the physical assets and the cyberspace**

In many smart enterprises the physical layer and the logistics layer (see Figure 1) will be designed for the ease and speed of connecting and disconnecting from each other. The vertical reparability will be largely attributed to the need of reconfiguration of the physical assets.

Justification: The growing need to configure and reconfigure physical assets to better support the changing product needs supported by the expanding digitisation and standardisation will lead to new system architectures. The new architecting will be characterised by the ease of vertical separability of the physical and the cyber layer of an enterprise.

***Conjecture* 5: Enterprise dichotomy**

Two extreme smart enterprise models are likely to emerge, one where the physical assets and logistics are tightly connected (of the type in Conjecture 3) and the other with vertical separability of the two layers (*Conjecture* 4).

Justification: The tight vertical connectivity or vertical separabilty models (a dichotomy) may emerge in the spirit of *Conjecture* 3 and *Conjecture* 4, respectively.

***Conjecture* 6: Greater horizontal connectivity and interoperability**

The degree of horizontal internal and external connectivity and interoperability of smart manufacturing enterprises will increase.

Justification: This will be driven by the need to reconfigure the physical and logistics assets within an enterprise and among different enterprises. Standardisation (*Conjecture* 9) will serve as an enabler in both layers. The growing volume and flow rate of data across a modern enterprise will naturally lead to adopting solutions supporting greater horizontal connectivity and interoperability of the systems accommodating the data flow.

Conjecture 7: Resource sharing

Sharing manufacturing and transportation resources across manufacturing chains will become a common practice.

Justification: The unprecedented degree of horizontal connectivity of smart enterprises (*Conjecture* 6) combined with the dynamics of the markets will facilitate sharing manufacturing equipment, transportation and other resources. Innovation of manufacturing equipment could benefit from resource sharing as companies may purchase equipment based on an explicit assumption that it will be shared.

***Conjecture* 8: Equipment monitoring, diagnosis and repair autonomy**

Diagnosis and prediction of equipment faults will become routine in smart manufacturing. In some cases autonomous repair may take place.

Justification: Monitoring of equipment generates data (*Conjecture* 1) supporting the diagnostic models (*Conjecture* 2) deployed to monitor and predict health status of the equipment and systems. Preventing faults from occurring and anticipation of the future faults will become a common practice.

***Conjecture* 9: Standardisation and collaboration**

Collaborative development of standards may naturally emerge to meet the emerging needs of integration and interconnectivity of enterprises.

Justification: The growing reliance on data (*Conjecture* 1), resource sharing (*Conjecture* 7) and the need for vertical separabilty (*Conjecture* 4) and horizontal connectivity and interoperability (Conjecture 6) will drive the need for standardisation and collaboration. The complexity of the tasks at hand will likely enhance collaboration. It would be useful to have parametric standards reflecting the readiness of an enterprise for horizontal and vertical connectivity and interoperability. Based on these metrics, an enterprise could be assigned a class, e.g. Class 4 (out of five classes) enterprise could easily engage in business with any other Class 4 or lower enterprises. Such standard would speed up enterprise reconfigurability and integration.

***Conjecture* 10: Cybersecurity and safety**

Cybersecurity and safety issues will remain a challenge to be continuously addressed.

Justification: Growing volumes and reliance on data (*Conjecture* 1) make cybersecurity paramount to the progress in smart manufacturing and business competitiveness. This is especially important as data assets will become a growing indicator of the market value of a company. The increasing degree of automation and system autonomy will raise the importance of human and machine safety. Condition monitoring solutions and warning systems (*Conjecture* 8) will gain importance. In fact, the commonality between solutions developed for equipment diagnosis and cybersecurity may be explored.

5.1 *How to accelerate the smart manufacturing transformation?*

A viable approach to increase effectiveness of the manufacturing transformation is in large-scale collaboration on the core issues attributed to the industries with the largest societal impact. Creation of an open development platform involving key industries could enable such collaboration, including development of data-driven models.

There is no doubt that open platforms will be realised at different scales. Research on collaborative manufacturing networks has demonstrated the value of tools in joint international projects. However, expanding the scope and scaling up the collaborative modelling tasks makes it a worthwhile effort. As in any collaborative venture, trust and revealing of information must be overcome. Getting deeper insights into the trust at smaller scale platforms would be the initial step to address sharing information and knowledge. Modelling at different scales is needed to attract industry, small and large, to a common collaboration table. In fact, making sure that small and medium enterprises join the table with large corporations is critical. The degree of engagement of small and medium size businesses in designing the enterprise of the future is variable across the world. While the small business entrepreneurship initiatives generally prevail in the United States, Asia and Europe have shown more interests in issues affecting the functioning small businesses. To make the progress diversity of ideas, cultures, needs and openness are needed. More details of the manufacturing transformation are discussed in Kusiak (2017a).

5.2 *Special note*

The year 2017 marks publication of the 55th volume of the *International Journal of Production Research* (*IJPR*). The history of the journal dates to 1961, when it was launched by the Institution of Production Engineers with four issues published. No volume was published in 1962, rather Volume 2 of *IJPR* appeared in 1963.

Subsequently Volume 25 with ten issues was published in 1987. This was the decade of flexible automation that remains of interest to many companies and research groups to these days.

Volume 50 with 24 issues appeared in 2012. Massive outsourcing and offshoring efforts dominated the manufacturing industry, lean production initiatives have blossomed and supply chain research was in a full swing.

Recent years have brought a renewed interest in manufacturing. Volume 55 of 2017 marks the reversal of some of the manufacturing initiatives followed in the previous years, e.g. rather than the offshore manufacturing, reshoring is taking place. Energy, sustainability, big data and cybersecurity dominate the news. It is reasonable to assume that volumes 75 and 100 will be published in 2037 and 2062, respectively. The new research directions will likely be discussed in the papers to come.

The Editorial published in the inaugural issue of the *IJPR* in 1961 presented a vision for the research to be disseminated. It included keywords such as production process, production policy, planning and control, productivity measurements and technology. There should be no surprise that the keywords such as computers and artificial intelligence that are prominent today were not mentioned then as they were in their infancy. Later years have offered progress in manufacturing technology, automation, computerisation, sensor proliferation, communication and cyber technologies that have made the manufacturing of today and shape the manufacturing of tomorrow.

6. Conclusion

Automated factories were envisioned and demonstrated decades ago. In general, the industry has retreated from pursuing the vision of total automation for valid business reasons. There is no doubt that some smart factories will be highly automated. However, smart manufacturing is not about the degree of automation of the manufacturing floor; it is about autonomy, evolution, simulation and optimisation of the manufacturing enterprise. The scope and time horizon of the simulation and optimisation will depend on the availability of data and tools. The level of ‘smartness’ of a manufacturing enterprise will be determined by the degree to which the physical enterprise has been reflected in the cyber space.

This paper offers a vision of smart manufacturing. Its essence was encapsulated in six pillars differentiating it from the manufacturing as we know it. The pillars were supported with ten conjectures characterising smart manufacturing. A special anniversary note was included.

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