Smart Manufacturing: Characteristics, Technologies and Enabling Factors

Article *in* Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture · January 2019

DOI: 10.1177/0954405417736547

4 authors:


Sameer Mittal
West Virginia University


Muztoba Ahmad Khan
West Virginia University


David Romero
Tecnológico de Monterrey


Thorsten Wuest
West Virginia University

Special Issue Article

Institution of MECHANICAL ENGINEERS

Journal of ENGINEERING MANUFACTURE

Proc IMechE Part B: J Engineering Manufacture
1–20

Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0954405417736547
journals.sagepub.com/home/pib
SAGE

Smart manufacturing: Characteristics, technologies and enabling factors

Sameer Mittal[1], Muztoba Ahmad Khan[1], David Romero[2] and Thorsten Wuest[1]

Abstract

The purpose of this article is to collect and structure the various characteristics, technologies and enabling factors available in the current body of knowledge that are associated with smart manufacturing. Eventually, it is expected that this selection of characteristics, technologies and enabling factors will help compare and distinguish other initiatives such as Industry 4.0, cyber-physical production systems, smart factory, intelligent manufacturing and advanced manufacturing, which are frequently used synonymously with smart manufacturing. The result of this article is a comprehensive list of such characteristics, technologies and enabling factors that are regularly associated with smart manufacturing. This article also considers principles of "semantic similarity" to establish the basis for a future smart manufacturing ontology, since it was found that many of the listed items show varying overlaps; therefore, certain characteristics and technologies are merged and/or clustered. This results in a set of five defining characteristics, 11 technologies and three enabling factors that are considered relevant for the smart manufacturing scope. This article then evaluates the derived structure by matching the characteristics and technology clusters of smart manufacturing with the design principles of Industry 4.0 and cyber-physical systems. The authors aim to provide a solid basis to start a broad and interdisciplinary discussion within the research and industrial community about the defining characteristics, technologies and enabling factors of smart manufacturing.

Keywords

Smart manufacturing, Industrie 4.0, Industry 4.0, cyber-physical systems, smart factory, intelligent manufacturing, industrial Internet, advanced manufacturing, digital manufacturing

Date received: 20 December 2016; accepted: 27 August 2017

Introduction

Smart manufacturing (SM), a term originated in the United States but increasingly used globally, has gained significant momentum in industry and academia in recent years. Many manufacturing systems are presenting themselves as SM systems (SMSs). SM is a set of manufacturing practices that use networked data and information and communication technologies (ICTs) for governing manufacturing operations.[1] ICTs deal with planning and control of production.[2] Traditionally, manufacturing was limited to a process or a sequence of processes through which raw material is converted into finished goods. However, the common understanding of manufacturing comprises much more. Manufacturing today considers the data-driven business operation at different levels leading to the growth of various paradigms in manufacturing, of which emerged SM.[3] Future SMS will possess unique properties of self-assembly to produce complex and customized products to exploit the new and existing markets.[4] SM uses information to continuously maintain and improve performance.[5] Several frameworks have been proposed in the SM realm. One of them is an accuracy assured framework, based on four factors, namely, physics conscious, operations planning, intelligent monitoring and on-machine shape measurement and error source estimation for an SMS.[6] Additionally, the President's Council of Advisors on Science and Technology (PCAST) has mentioned in its report that the share of gross domestic product (GDP) by

[1]Department of Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV, USA
[2]Tecnológico de Monterrey, Mexico City, Mexico

Corresponding author:
Thorsten Wuest, Department of Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV 26506, USA.
Email: thwuest@mail.wvu.edu

manufacturing has been decreasing recently, and advancement in science, technology and innovation will help the United States become a global leader in manufacturing.[7] However, despite the rapidly growing body of literature, applications and use of the term smart manufacturing in academia and industry, there is still a lack of commonly accepted understanding about what defines a manufacturing system as being "smart." SM and other systems such as intelligent manufacturing, advanced manufacturing/advanced manufacturing systems,[1,7,8] additive manufacturing,[9] digital manufacturing,[10] smart factory[11] and Industry 4.0[12] are actually being used synonymously on occasion by some authors.

The overarching question remains, "What aspects make a manufacturing system smart?" The literature on SM has suggested various characteristics, technologies and enabling factors that define a manufacturing system as "smart." This article investigates the suggested characteristics, technologies and enabling factors through a literature review and tries to form clusters for the homogeneous items. This work collects a comprehensive list for each of the items based on a literature review of 83 articles that use the specific term "smart manufacturing."

Research methodology

The schematic of the research methodology used in this article has been shown in Figure 1. First, the electronic journals of Taylor and Francis (T&F), Science Direct (SD), Wiley, Emerald, SAGE and Springer, and additionally Google Scholar (GS) and Google, were searched with the keyword "smart manufacturing." In the second step, the title and abstracts of the articles found from step 1 were read for the initial screening. It was also made sure that these articles/reports are in English only. The literature available in other language was not considered. In the third step, all the articles found from initial screening were thoroughly reviewed to find their relevancy with SM. After this step there were 67 articles and 16 reports that were found relevant. Finally, the list of characteristics, technologies and enabling factors was prepared with the help of relevant literature. In this study, we focused on characteristics, technologies and enabling factors specifically associated with SM and kept characteristics, technologies and enabling factors associated with similar terms, for example, Industry 4.0, smart factory, advanced manufacturing, cyber-physical production system (CPPS) and other similar manufacturing initiatives out of our focus. The reason for this rather strict system boundary is that it allows us to create a comprehensive list of SM-specific characteristics, technologies and enabling factors, which later may be compared to the aforementioned concepts. This comparison will help analyze the similarities and differences among them and determine whether they are indeed synonymous with SM or whether there are certain distinct differences. This article is structured as follows: first, a literature review of current indexed scientific articles containing the term "smart manufacturing" is presented along with a comprehensive list of SM-associated characteristics, technologies and enabling factors. The characteristics, technologies and the enabling factors are classified based on how they are defined in the reference article and how the authors interpret them.

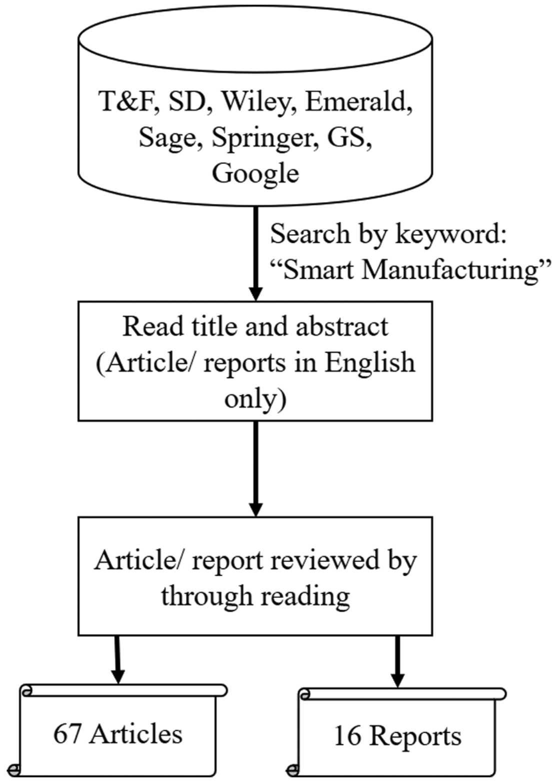

Figure 1. Schematic for methodology adopted in this article.

Interestingly, more than 95% of these articles and reports were published in and after 2013. This might be an indication of the novelty of SM (compared to more established terms such as "intelligent manufacturing" or "Industry 4.0") and shows how fast its popularity in academia and industry has increased within recent years. There are several gray papers and reports published by federal agencies, for example, National Institute of Standards and Technology (NIST) and other institutions, for example, the Smart Manufacturing Leadership Coalition (SMLC) leading the newly established Clean Energy Smart Manufacturing Innovation Institute (CESMII). This gray literature was used mainly as motivation for this research and to define the system borders.

The following section defines and sensibly clusters the individual characteristics, technologies and enabling factors. The authors' clustering was based on the use of established ontologies in relation to SM vocabulary (e.g. glossaries) and the consideration of the semantic distance between the terms being classified. Semantic similarity in this context is understood as

> a metric defined over a set of documents or terms, where the idea of distance between them is based on the likeliness of their meaning or semantic content as opposed to similarity which can be estimated regarding their syntactical representation (e.g. the string format).[13]

Finally, a condensed list of characteristics, technologies and enabling factors associated with SM is presented as a basis for further discussion within the SM community. In a first attempt to compare the identified SM identifiers with other popular manufacturing initiatives, it is discussed how they compare to established design principles of (1) Industry 4.0 and (2) cyber-physical systems (CPSs). The various manifestations associated with these principles are also stated. The article concludes by providing a brief overview of the results and a discussion of the limitations of the study.

Literature review

Researchers have previously identified a variety of characteristics, technologies and enabling factors associated with SM. Some of these characteristics, technologies and enabling factors have been specifically mentioned as such. However, this is not always the case, and thus, the authors identified additional items that can be associated with these categories by thoroughly going through the relevant material. SMLC has suggested some SM platforms considering integration of different technologies in the system,[1,14] From the facility level, SM is the vertical and horizontal integration of manufacturing systems.[15] Therefore, an SMS should be aware of the state of its predecessor machines, successor machines and the machines running in parallel. A computational-based learning system that incorporates interconnected data, integrated automation and intelligent information has also been used in literature[16] to create an SMS. Nevertheless, in this case, the SMSs' scope is limited to computation. A strategic model for SM considering agility as the goal and a model that can be adapted to other goals has been presented by NIST.[17] Agility, asset utilization and sustainability were considered as the metrics for the classification of SMS.[18] Similarly, there are other characteristics and technologies that have been used to define SM. Four steps toward SM have also been mentioned:[19] (1) establish forums where problem definitions can be discussed, (2) develop cyber-platforms, (3) data sharing and (4) introduce SM-friendly policies. However, there is no research that presents a comprehensive list of characteristics, technologies and enabling factors that make a manufacturing system "smart." The set of characteristics, technologies and enabling factors, which are required in an SMS, will differ. For example, a smart pharmaceutical system focused on improving drugs and other medicines may not require visual technologies such as augmented reality (AR). However, another healthcare system that, for example, develops artificial limbs may profit from using this technology. Therefore, this answers the question, whether an SMS has to incorporate all the identified characteristics, technologies and enabling factors simultaneously or whether it is sufficient to define a manufacturing system as smart when only a certain selection is used. The degree of SM engagement often varies significantly between SMEs and large corporations. Generally, it can be observed that only few SMEs, while often having partly automated processes installed, have an IT-based production management system in place. However, a majority of the large, multinational corporations already incorporate IT systems for real-time communication among other things. Of all companies, only a handful of high-tech organizations such as Tesla, LG, Samsung and Siemens already have a customized production based on Internet of Things (IoT) CPS in use.[20]

To create a common basis for the following discussion, the terminology will be reviewed. A *characteristic* may be defined as a property that is particular to something and can be varied to make elements look similar or different. Examples for characteristics are modularity, heterogeneity and flexibility. *Technology*, however, is the use of science for practical purposes. This includes but is not limited to data analytics and three-dimensional (3D) printing. Technologies are also the identifiable parts of a larger construction that can provide a particular function or a group of related functions. *Enabling factors* are the standards and managerial practices that need to be maintained. For the successful implementation of characteristics and technologies in SM, this includes, for example, laws and regulations, innovative education and training of employees. This article presents a discussion on various SM-related characteristics, technologies and enabling factors that are essential for the installation and operation of an SMS. Table 1 presents a list of 27 characteristics identified in literature defining SM (or an SMS). The items will be analyzed for clustering in the next section.

Table 2 presents a list of 38 technologies that are associated with SM. Some of these technologies can be merged and clustered together as certain items are rather closely related. This is motivated by two main reasons. First, different authors may use different terminology, as no established ontologies exist in the field of SM. Second, the level of detail that authors decided to use in their respective publications to describe relevant subcategories of technologies differs significantly as well. The clustering of closely related items based on their "semantic similarity"[13] is addressed in the following section.

In addition to the various characteristics and technologies, there are a set of enabling factors, which facilitate the successful implementation of characteristics and technologies in SM.[3] These may also be referred to as guidelines that an organization has to maintain to

Table 1. List of characteristics associated with smart manufacturing.

S. no.	Characteristics	Reference(s)
1	Digital presence	10,21
2	Modularity	10
3	Heterogeneity	10,21
4	Scalability	10,21
5	Context awareness	10
6	Autonomy	10,21
7	Adaptability	21,22
8	Robustness	23,24
9	Flexibility	20,22
10	Fully automated	16,20
11	Asset self-awareness	23,25
12	Interoperability	10,21
13	Networkability	10,16,22,26
14	Information appropriateness	23
15	Integrability	23
16	Sustainability	1,4,18,23,25,27,28
17	Compositionality	21
18	Composability	21
19	Proactivity	23
20	Reliability	17,22,29
21	Agility	17,18,25,27
22	Responsiveness	17
23	Accuracy	6
24	Reusability	24
25	Decentralized	22
26	Distributed	22
27	Resilience	25

adopt SM characteristics and technologies. Table 3 presents a list of seven enabling factors that may be associated with SM. It has to be considered that this selection is solely based on the available literature and (a) is most likely not complete and (b) the different enabling factors are not necessarily always required in combination.

The items presented in Tables 1–3 are derived from current literature. As mentioned, this leads to some of these items being rather similar. In the next section, we present a perspective on how the different characteristics, technologies and enabling factors can be clustered to create a consolidated list.

Analysis

The presented characteristics, technologies and enabling factors have been mentioned and described in current SM literature. However, the detailed definitions, as discussed in this article, suggest that some of these characteristics, technologies and enabling factors are used synonymously and may be merged to present a more focused result. In the following section, the previously identified characteristics, technologies and enabling factors (Tables 1–3) are critically discussed and a clustering is proposed to develop a more comprehensive and targeted list. Clusters will include a set of similar characteristics or technologies, or a combination of characteristic and technologies. It is also important to understand that the clusters may contain technologies and characteristics at the same time but after final review are considered to belong in either a technology or characteristic cluster. This is due to the overlaps in terminology and the strong

Table 2. List of technologies associated with smart manufacturing.

S. no.	Technology	Reference(s)
1	Intelligent	16,20,29
2	Intelligent control	6,20
3	Energy saving/efficiency	4,21,15,20,30,31
4	Cyber security	23,29,30
5	Holograms	20,30
6	VR	30,3,32
7	AR	30
8	Real-time communication/ data	20,25,33
9	Big data	20
10	Cyber-physical infrastructure	21,20,23
11	CPS/CPPS	20,30,34
12	IoT/IoS/IIoT	20,30
13	Advanced manufacturing	1,7,21,22
14	Cloud computing/cloud manufacturing	1,30,35
15	3D printing/additive manufacturing	9,20,30
16	Smart sensors	20,28
17	Smart product/part	20,36
18	Data analytics/big data analytics	10,21,37,38,39,28
19	Predictive analytics	37,28
20	Data visualization	3,40
21	Modeling	4,40
22	GIS	38
23	Simulation	4,41,28
24	Forecasting	4
25	ERP	42
26	RFID	43
27	Machine learning	6,37,38,44,45,28
28	SCM	42,28
29	MES	42
30	PLM	27,42
31	Smart materials	4,46
32	Interface (SCOR, DCOR, MESA, ISA 95/88)	42,28
33	CAM, CAD, CAx	27
34	Operations planning	6
35	IT-based production management	20
36	Tracking and tracing	20,47
37	Knowledge decision-making techniques	3,48,25
38	SPC	3

VR: virtual reality; AR: augmented reality; CPS: cyber-physical system; CPPS: cyber-physical production system; IoT: Internet of Things; IoS: Internet of Services; IIoT: Industrial Internet of Things; 3D: three-dimensional; GIS: Geographic Information Science; ERP: enterprise resource planning; RFID: radio-frequency identification; SCM: supply chain management; MES: manufacturing execution system; PLM: product lifecycle management; SCOR: Supply Chain Operations Research; DCOR: Design Chain Operations Reference; MESA: Manufacturing Enterprise Solutions Association; CAM: computer-aided manufacturing; CAD: computer-aided design; CAx: computer-aided X; SPC: statistical process control.

Table 3. List of enabling technologies associated with smart manufacturing.

S. no.	Enabling factor	Reference(s)
1	Law and regulations	3,49
2	Innovative education and training	3,41
3	STEP AP 242	50,35,42
4	Knowledge workers	4,51
5	CMSD	25
6	MTConnect	37,42,52
7	Enterprise integration	41

CMSD: core manufacturing simulation data.

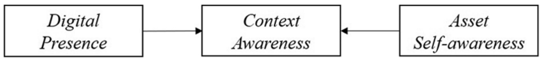

Figure 2. Visual representation of context awareness cluster with its corresponding characteristics.

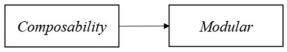

Figure 3. Visual representation of modularity cluster with its corresponding characteristic.

interdependencies between various items. While this is not ideal and adds additional complexity, it is a reflection on the inherit complexity of the topic and the importance of starting to work toward a common understanding and terminology. The enabling factor clusters, dealing with guidelines for organization or people, cannot have characteristics and technologies, and similarly characteristics and technologies should not contain enabling factors.

In the forthcoming analysis, the following format has been chosen for better illustration and transparency: characteristics are represented in *italics*, whereas technologies are represented in **boldface**; enabling factors do not have a different notation. Each cluster is also illustrated according to a similar visual representation method used in literature.[3] There were some items that could have been arguably placed in another cluster; nevertheless, they are placed in a specific cluster because of the discussion below. For some items, the authors used their subjective judgment on determining the most suitable cluster. However, the authors fully acknowledge that one might argue that the respective item(s) might fit into another cluster as well based on the individual background and experience. Therefore, the items in question are highlighted in the figures with a gray background in the following illustrations of clusters.

Characteristics clusters

Context awareness. *Context awareness* is an important characteristic of an SMS,[10,53] and it can be seen as a combination of the following attributes:

1. Identity: An SMS should have a unique identity. As an SMS often operates in a digital environment, we may say that an SMS should have its own *digital presence*, thus providing with a unique identification in the digital world, for example, a network interface address.[10] Therefore, digital presence is inherent when we consider context awareness.
2. Location: It is used to describe the physical location of the system itself or sub-systems within.
3. Status: This is used to describe the present state of the activities that are being carried within the SMS. *Asset self-awareness* will also mean that the SMS should be able to know about its present state.[23]
4. Time: The SMS should be able to define its timely priorities, and it might even need to consider the local time. Figure 2 presents the characteristics that make the *context awareness* cluster.

Modularity. *Modularity* is the property of a system by virtue of which a unit can be decomposed into components that can be combined to form different configurations.[10] *Composability* is the property of the system when it could be developed from its sub-systems.[21] As both these properties consider a unit being made from sub-units and by modularity, we can have a different unit arising; therefore, composability may be considered as a part of modularity. Figure 3 visually represents composability that is included in the modularity cluster.

Heterogeneity. *Heterogeneity* considers the diversity and dissimilarities in the units and components. However, it does not consider the combination of units such as modularity, and as a result, it should be considered as a separate characteristic.[10]

Compositionality. *Compositionality* is the property that deals with the understanding of the whole system based on the definition of its components and the combination of the constituents.[21] As neither modularity nor heterogeneity deal with the system or component definitions, compositionality should be considered as a separate characteristic.

Interoperability. *Interoperability* is the characteristic due to which, system units would be able to exchange and share information with each other,[10,21] With the help of *networkability*, systems are able to collaborate in different process-related aspects, and for this collaboration, they have to allow each other to share and exchange information.[10] Similarly, *distributed* systems allow the information and data of one system to be accessed by other systems in the network. Therefore, networkability and distributed characteristics of systems are covered by interoperability. *Information appropriateness* describes that information is available, accessible and understandable when needed; this should be a characteristic of information to be shared, otherwise the information will be of no use.[23] *Integrability* is the characteristic due to which different units can be integrated, but two units are integrated only if they have an access to each other's information. Therefore, this characteristic of integrability is included in interoperability.[23] *Decentralized* is the characteristic by virtue of which SM can be operated by other attached units, and consequently it may be considered as part of interoperability. However, integrability is different from modularity because modularity physically combines the systems resulting in a new configuration, whereas integrability is inclined toward the exchange of information between two systems and therefore it is a part of interoperability. It is important to discuss why interoperability and cloud computing/manufacturing are different. Cloud is like a database where information can be saved and accessed by all the systems that are part of this cloud. In contrast, interoperability also allows systems to access data and information, which has not been shared, for example, in the cloud. Figure 4 visually represents all the characteristics present in the *interoperability* cluster.

Technology clusters

Intelligent control. An important characteristic of manufacturing systems is the speed of response to events. *Responsiveness* may be considered as the ability of an SMS to speedily provide the desired products to the customers.[17] Peer-reviewed papers refer to this response using various terms. *Agility* is the ability of a system to respond to external influences; in SMS, this could be the response to market changes.[17] *Scalability* is considered as the property by which it can easily handle the fluctuations in load,[10] hence the change in response. *Adaptability* describes the ability of the system to decide about its own diagnosis, prognosis and the best system performance even when it has uncertain information.[54] A system can be considered to have a high level of *robustness* when it can perform well under uncertain conditions,[23] and it possesses *flexibility* when it can adapt to changes in the external environment.[55] *Reliability* is the ability to perform activities as expected, and therefore it also makes the results predictable.[17] *Accuracy* is the ability to provide the result exactly or very close to the actual result. The definitions of all characteristics appear homogeneous and therefore are placed in the same cluster.

With the help of **intelligent** technology, a system is able to change its action based on its own experience,[56] and if it possesses **intelligent control** technology, it can make use of, for example, artificial intelligence techniques to control its mechanisms[56] and is able to be reliable and accurate. These characteristics and technologies converge toward being responsive to changes and may use artificial intelligence techniques for doing so, and therefore, they should be considered as a part of intelligent control. A manufacturing unit possesses *autonomy* if (a) it can adapt with feedback and pursue its activities to achieve the objective [10] and (b) the unit wants the feedback mechanism to work. It will need the technology of intelligent control; therefore, autonomy should be a part of intelligent control. A system is said to be *fully automated* if it can do its own work completely, but the extent of automation may vary from system to system. For a system to be fully automated, it will also need some intelligent control mechanisms. The more sophisticated the control mechanisms, the higher the degree of automation. Therefore, this characteristic should also be covered by intelligent control. *Proactivity* is the characteristic that can help units eliminate failures before they happen by sensing the situation.[23] As this characteristic considers sensing and controlling the mechanisms of the system, it will need intelligent control mechanism. Therefore, we can consider it as a part of intelligent control. However, proactivity senses the present situation that might involve data, so this characteristic might be involved in the data analytics cluster as well. Figure 5 shows the different characteristics and technologies included in the **intelligent control** cluster. The reason why machine learning may not be a part of intelligent

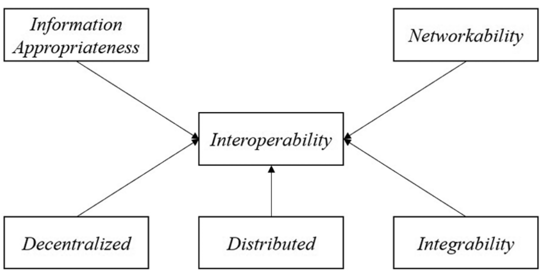

Figure 4. Visual representation of interoperability cluster with its corresponding characteristics.

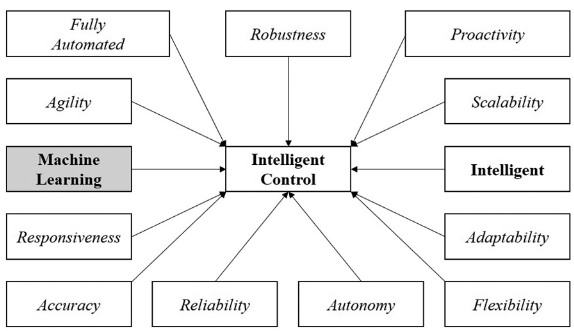

Figure 5. Visual representation of intelligent control cluster with its corresponding characteristics and technologies.

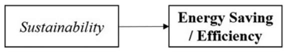

Figure 6. Visual representation of energy saving/efficiency cluster with its corresponding characteristic.

control and might be a part of data analytics has been discussed in the data analytics section.

Energy saving/efficiency. Products and processes are said to possess *sustainability* if they are reusable and cause minimum environmental footprints,[23] thus making the products and processes more economical, social and environment-friendly. The importance of energy cost savings through SM has been discussed frequently, and energy saving is among the main drivers for SM.[15] A sustainable SM process for extracting olive oil has also been proposed.[57]**Energy saving/efficiency** is the technology due to which the energy required to provide a product and service can be reduced. Various studies have been done to decrease the use of energy in manufacturing systems.[30] If a system can reuse its products, then the amount of energy required will decrease in most cases. Thus, sustainability can arguably be seen as part of energy saving. Although researchers have considered energy saving/efficiency on par with the other technologies, it may be considered as a necessity for any manufacturing system and not only SMS. The choice of terminology "energy saving" as a technology was derived from literature and as such not altered based on the employed methodology. Figure 6 presents the characteristics included in the **energy saving/efficiency** cluster.

Cyber security. Data should be secured from cyber threats. As SM is largely based on digitization and data-based services, **cyber security** is an integral technology for SMS.[53] Even though this characteristic also involves data, it should still be considered separate from interoperability because interoperability is about data sharing and availability, whereas **cyber security** is about data privacy and security.

Visual technology. **Hologram** is a technology that makes use of a 3D image formed by a light field in a 3D space.[58] **Virtual reality (VR)** described the technology to create 3D images with the help of a computer and the interaction in that space with the help of electronic devices for the user to feel as if he or she has been "immersed in a synthesized environment."[59,60]**Augmented Reality (AR)** is a technology that can superimpose a computer-generated 3D numerical format in the real world, but one cannot interact with it.[61,62] Since all these technologies encompass the visual representation of an object, built with the help of electronic devices, they may be considered as a part of the **visual technology** cluster.[61]

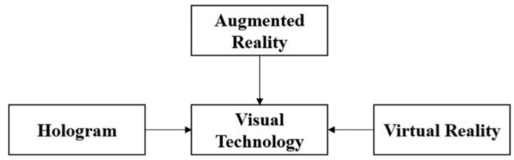

Figure 7. Visual representation of visual technology cluster with its corresponding technologies.

Figure 7 shows the various technologies included in **visual technology** cluster.

Data analytics. **Big data** is the technology that can analyze large data sets including real-time data that are difficult to analyze by traditional methods. **Data analytics** generally deals with turning the volume, variety, velocity and veracity of data into actions and insights within a manufacturing system.[21,62] A demonstration showing use of simulation in data analytics and data visualization has also been presented.[40] As **data analytics** can deal with a very high volume of data, the popular technology "big data" can be understood as being part of this technology; since data analytics can also process a high velocity of data, it can communicate in real-time with the customers. **Machine learning** involves the self-teaching of computer programs based on their experiences and pattern recognition;[63] it does not need any human involvement so it might be included in intelligent control as well. However, we are considering that it also recognizes patterns when exposed to new data, and therefore, it should be a part of the data analytics cluster.

Predictive analytics finds results with finding some results with the help of measurable variables in the data, and data mining is the field of exploring large amounts of data.[64] Since predictive analytics also deal with analysis of data, it is included in data analytics. **Data visualization** is the technique of representing data with the help of graphs and other visual representations, which can lead to the development of graph patterns to analyze the data.[65] It should also be considered as a part of data analytics rather than the visual technologies cluster as the latter focuses on technology, whereas data visualization focuses on the content. Geographic Information Science (GIS) provides information about space and time. This information helps in data visualization and data analysis.[38] It could be discussed whether GIS should be a part of smart part/product/material as well because there could be some sensor attached to the system to store the data.

Modeling is the representation of a real-world scenario by a mathematical expression and/or a simplification of the real-world system. **Simulation** uses a model to generate data and these data could be analyzed later. **Forecasting** deals with the prediction of what could happen in the future with the help of available data.

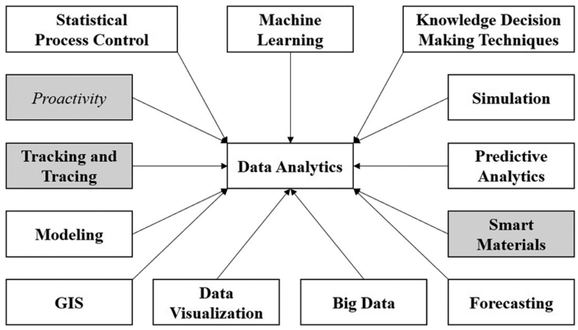

Figure 8. Visual representation of data analytics cluster with its corresponding characteristics and technologies.

Since all three, modeling, simulation and forecasting, rely on data to make decisions, they are included in the data analytics cluster. **Knowledge decision-making techniques** are techniques such as multi-criteria decision-making (MCDM), mathematical programming techniques and artificial intelligent techniques[66] that help make decisions. As these techniques also help make decisions based on data, they should be involved in data analytics.

Statistical process control (SPC) is a process of controlling quality through advanced statistics. It is being used in a manufacturing environment for a long time, but is still valid and widely used today to control and monitor operations. It uses data and derives suggestions for improvements, and thus should be considered as being part of data analytics. Statistics has been used in a variety of manufacturing applications, for example, in smart chemical process diagnosis.[24] Figure 8 presents the various technologies that are placed in the **data analytics** cluster. Items such as *proactivity*, **tracking and tracing** and **smart materials** that are a part of different clusters but could have been a part of this cluster are shown with a gray background.

CPS/CPPS. **CPSs/CPPSs** are often used interchangeably[21] and describe technologies used by computer algorithms to solve and work with physical mechanisms/components.[67]**CPPS** is an applied form of **CPS** in production.[68] We will consider all these technologies as **CPS**. Figure 9 shows the technologies present in the **CPS/CPPS** cluster.

IoT/IoS. The **IoT** enables the communication between physical and Internet-enabled devices[30] and can be used to improve the existing manufacturing systems. For example, a scheduling model for a hybrid workshop facilitated by IoT has also been proposed.[69] There are many varieties used commonly, for example, when **IoT** capabilities are seen as services, they are referred as Internet of Services (IoS).[70] Although both **CPS** and **IoT/IoS** consider physical and virtual world, a major difference is that the computer algorithms may or may not use the Internet. There are examples when **CPSs** have been considered as a foundation for **IoT/IoS**.[71] However, this is not necessarily the case for all applications; therefore, they are considered as separate technologies in this case. In this article, we are considering IoT as ubiquitous in the global sense and as a combination of national IoT, industrial IoT and local IoT.[72] Figure 10 shows that **CPS** might have been placed in **IoT/IoS** cluster.

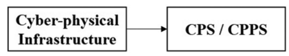

Figure 9. Visual representation of CPS/CPPS cluster with its corresponding technology.

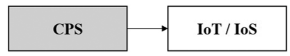

Figure 10. Visual representation of IoT/IoS cluster with its corresponding technology.

Advanced manufacturing. **Advanced manufacturing** is the technology that can integrate technology-based production systems such as flexible manufacturing system (FMS), reconfigurable manufacturing system (RMS), computer integrated manufacturing (CAM) and additive manufacturing.[8] Overall, advanced manufacturing may be defined as integration of different production technologies, and therefore, it should not be considered as a technology for SM. Rather it could be an important discussion if various advanced manufacturing systems could be referred to as SMS. One possible distinction is that SM focuses more on the data aspects of manufacturing (data analytics), whereas advanced manufacturing is more focused on physical manufacturing technology.

Cloud manufacturing. **Cloud manufacturing** is driven by **cloud computing**[62] that can, for example, use real-time demand to decide the production planning and scheduling. **Data analytics** may be considered as a part of cloud manufacturing, but as the applications of data analytics are so diverse, we should not consider it to be a part of cloud manufacturing. **Real-time communication** is the technology that would enable the users to exchange data with the systems in real-time. As it involves exchange of information between system and humans, it is not a part of interoperability. Figure 11 shows various technologies in the **cloud-manufacturing** cluster. **Cloud manufacturing** has also been considered to be supported by IoT, VR and cloud computing,[73] but again since IoT and VR can stand as independent technologies, this article considers them as different technologies.

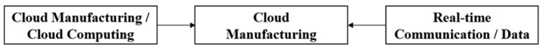

Figure 11. Visual representation of cloud manufacturing cluster with its corresponding technologies.

3D printing/additive manufacturing. **3D printing/additive manufacturing** is the technology that can print a 3D image into an object with the help of laser beam, electron beam and so on; and as the objects are printed layer by layer, this technology is also referred to as additive manufacturing.[53]**Additive manufacturing** is often referred to as being part of the **advanced manufacturing** domain.[8]

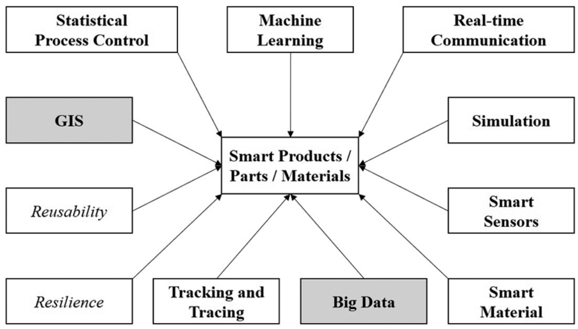

Figure 12. Visual representation of smart products/parts/materials' cluster with its corresponding characteristics and technologies.

Smart products/parts/materials. *Reusability* is the property of products/parts/materials by which they can be recycled or used again in the system. It can be discussed whether reusability should be a part of energy saving/efficiency or smart products/parts/materials. If one considers the recycling part, then reusability can be included in energy saving; but if it is considered as a characteristic of a material that can change its configuration to be reused in the same form or other, then it is a smart material. In this article, we consider it as characteristic of smart material. *Resilience* is the ability by which a product/part/material would be able to retain its original form. Resilience can be placed in the intelligent control cluster because a part may require intelligent control to return in its original form. Nevertheless, it could be an inbuilt characteristic of smart materials as well.

Tracking and tracing is the technology by which one can find the past and present locations of unique objects as information-carrying identities.[74] Nevertheless, we need some (sensing) technology, which can help monitor tracking and tracing, and these sensors are referred to as **smart sensors**. Advanced temperature sensors and smart sensors have been used in production of hydrogen from methane.[75] Other applications include the use of anti-metallic radio-frequency identification (RFID) in manufacturing environments;[8] printed circuit boards[76] have also been demonstrated. When the smart sensors have processors and software for an efficient exchange of data, they are called as **smart products/parts**.[77] Use of RFID for tracking work-in-progress in shop floor has also been shown.[78] **Tracking and tracing** may also be used to provide data regarding location; and if that data are used for analysis, then it could be considered as a part of the data analytics cluster as well. **Tracking and tracing** could also be replaced by **tracking and tracing** *in real time*, as we can track the location of objects in the real time. However, in this article, **real-time communication** is considered as a separate technology and it has been placed under the umbrella of cloud manufacturing.

Smart materials can sense the change in environment and operations with the help of sensors and can take the corrective actions using actuators,[79] and they can also provide data for analysis as well, which may lead to improved part design.[80] Since smart materials require the use of sensors and actuators, they should be considered to be in the same cluster. Smart materials may also have the ability to change their structure as a response to external stimuli. A review of smart materials such as piezoelectric devices and shape memory alloys and their uses in industry has also been conducted.[81] Therefore, the containing cluster is named smart products/parts/materials. Figure 12 shows various characteristics and technologies that are a part of this **smart products/parts/materials'** cluster.

IT-based production management. Enterprise resource planning (**ERP**) is the information system that helps integrate and coordinate different parts of a business, such as marketing, inventory and human resources.[82] Supply chain management (**SCM**) is the flow of information, material and finance from one member to another.[83] Manufacturing execution systems (MESs) are IT-enabled systems that manage all changes happening to the product from raw material to finished good.[84] Product lifecycle management (PLM) is about effectively managing a product through its entire lifecycle.[85]

Operations planning is the planning of all activities of an organization to achieve the final objective. It seems that life of a product, when coordinated by an IT system, could be considered as MES, while MES, ERP, SCM and operations planning could be seen as tools to connect everything happening within the organization through the help of IT. For this reason, we include these technologies in the cluster **IT-based production management**. Computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided technology (CAx) and so on are tools that allow to design, analyze and facilitate the design and production.[86] Therefore, these CAx tools are included in the IT-based production management cluster as well.

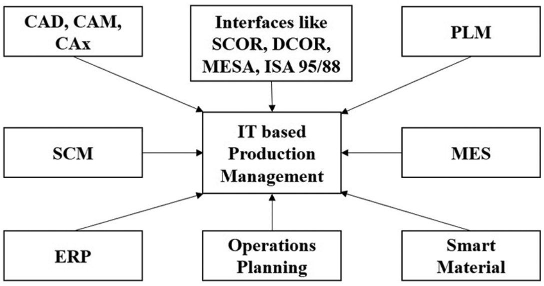

Figure 13. Visual representation of IT-based production management cluster with its corresponding characteristics and technologies.

Interfaces and high-level frameworks such as Supply Chain Operations Research (**SCOR**),[87] Design Chain Operations Reference (**DCOR**),[88] Manufacturing Enterprise Solutions Association (**MESA**) and **ISA 95/88**[89] consider the various levels of business processes and provide a computer-based package support. These should also be considered within the IT-based production management cluster. Figure 13 presents various technologies cumulated within the **cluster IT-based production management**. Digital manufacturing is the integration of technologies such as CAD, CAM, VR, ERP and modeling and simulation;[90] however, this article discusses why they could be clustered in different groups of technologies.

Enabling factors

Characteristics and technologies are not the only platform required for SM. There are also standards and aspects of organization culture to be considered for a successful transformation toward SM. NIST has also presented some of the characteristics and technologies discussed in this article and considered them as standards.[91] However, this article has considered characteristics, technologies and enabling factors (similar to standards referred to by NIST) as different groups and has tried to merge the ones that overlap. In the following section, selected standards and aspects of organizational culture associated with SM in literature, referred to as enabling factors, are discussed.

Law and regulations. There are various laws and regulations such as environmental laws,[92,93] intellectual property rights and labor law that an organization has to follow depending on the nature of its work. These laws should be strictly followed for continued operation of an organization.

Innovative education and training. Education should help an individual to not only do their own work but also think about how the product or service he or she is working for can be improved for the benefit of the end user. This knowledge and innovation mindset can only be instilled in the workers with the help of proper training and entrepreneurial culture. Therefore, knowledge workers should be a part of innovative education and training. For example, a case study presents the importance of people and their training in SM at Alcoa.[51] Figure 14 shows the cluster for innovative education and training.

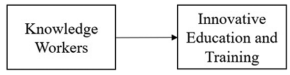

Figure 14. Visual representation of innovative education and training with its corresponding enabling factor.

Data sharing systems and standards. International Organization for Standardization (ISO) has defined STEP AP 242 and other STEP modules as universally standardized information models that can be used to exchange data and designs on common computer formats by various organizations.[50] Similarly, core manufacturing simulation data (CMSD) can share simulation data.[25] Enterprise integration also facilitates data sharing between small and medium enterprises (SMEs) and original equipment manufacturers (OEMs). A web-based visualization tool for energy management, following ISO 50001, has also been proposed.[94] All these organizations such as STEP AP 242 and CMSD are working to provide a common platform for exchange of information, and therefore, they might be considered as the standards for different data sharing systems and thus could be clustered in data sharing systems and their standards. The selected systems are some of the examples, as there are other systems available and in use with SMSs. The selection of these specific examples is again based on the identified reference in literature.

Interoperability is different from data sharing systems and their standards because interoperability is the characteristic to share data and access a system in the network, whereas data sharing systems and their standards would provide the license to do so. This is a standard platform set by the manufacturing industry to receive information from numerically controlled machines that could later be used for data analytics. Figure 15 shows the cluster of data sharing systems.

Discussion

From our analysis in section "Analysis," we can observe that some of the identified characteristics act as building blocks of a technology, but the definition of technologies does not allow them to merge in a characteristic cluster. However, both technology and characteristic could be a part of another technology cluster. As a result, we have a lower number of characteristic

Table 4. Clusters mentioning the names and numbers of characteristics and technologies.

Clusters	Name of characteristic(s)	Name of technology(ies)	No. of Char.	No. of Tech.	Total
Compositionality	Compositionality		1		1
Context awareness	Digital presence, context awareness, asset, self-awareness		3		3
Heterogeneity	Heterogeneity		1		1
Interoperability	Interoperability, networkability, information appropriateness, integrability, decentralized, distributed		6		6
Modularity	Composability, modularity		2		2
3D printing/additive manufacturing		3D printing/additive manufacturing		1	1
Cloud manufacturing		Real-time communication/data, cloud computing/cloud manufacturing		2	2
CPS/CPPS		Cyber-physical infrastructure, CPS/CPPS		2	2
Cyber security		Cyber security		1	1
Data analytics		Big data, data analytics/big data analytics, predictive analytics, data visualization, modeling, GIS, simulation, forecasting, machine learning, knowledge decision-making techniques, statistical process control		11	11
Energy saving/efficiency	Sustainability	Energy saving/efficiency	1	1	2
Intelligent control	Scalability, autonomy, adaptability, robustness, flexibility, fully automated, proactivity, reliability, agility, responsiveness, accuracy	Intelligent, intelligent control	11	2	13
IoT/IoS		IoT/IoS/IIoT		1	1
IT-based production management		ERP, SCM, MES, PLM, interface (SCOR, DCOR, MESA, ISA 95/88), CAM, CAD, CAx, operations planning, IT-based production management		8	8
Smart product/part/material	Reusability, resilience	Smart sensors, smart product/part, RFID, smart materials, tracking and tracing	2	5	7
Visual technology		Holograms, VR, AR		3	3

3D: three-dimensional; CPS: cyber-physical systems; CPPS: cyber-physical production system; GIS: Geographic Information Science; IoT: Internet of Things; IoS: Internet of Services; IIoT: Industrial Internet of Things; ERP: enterprise resource planning; SCM: supply chain management; MES: manufacturing execution system; PLM: product lifecycle management; SCOR: Supply Chain Operations Research; DCOR: Design Chain Operations Reference; MESA: Manufacturing Enterprise Solutions Association; CAM: computer-aided manufacturing; CAD: computer-aided design; CAx: computer-aided X; RFID: radio-frequency identification; VR: virtual reality; AR: augmented reality.

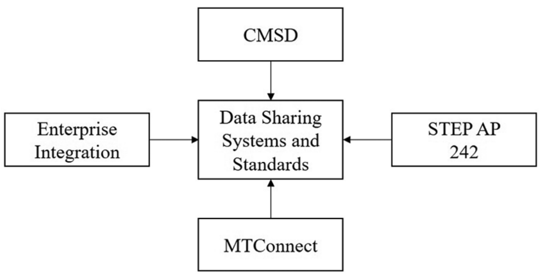

Figure 15. Visual representation of data sharing systems and their standards with corresponding enabling factors.

clusters and a higher number of technology clusters. It can also be seen that the **intelligent control** cluster consists of 12 characteristics, namely, *scalability, adaptability, flexibility, autonomy, fully automated, proactivity, robustness, reliability, agility, responsiveness, accuracy* and two technologies **intelligent** and **intelligent control**, thus making it the biggest cluster. Table 4 presents a comprehensive overview of the names and numbers of characteristics and technologies in each cluster. However, while Table 4 presents the clusters for characteristics and technologies, it does not include enabling factors. The main reason for this omission is that the

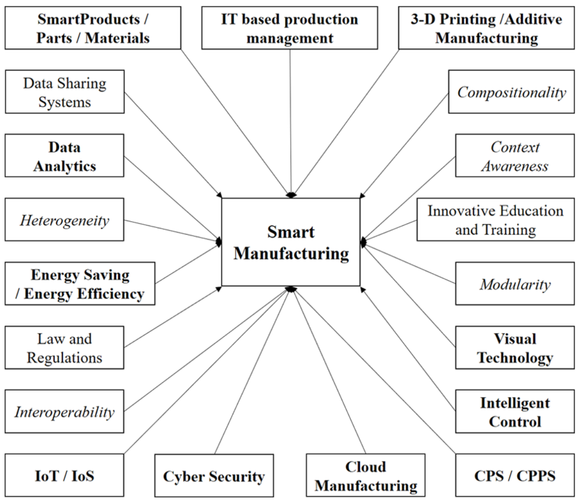

Figure 16. Visual representation of all characteristics and technologies that can define an SM.

enabling factors are more of a foundational aspect and that just a few of the identified articles actually referred to them. When the body of literature on SM expands in the future as expected, it might be possible to include enabling factors in a joint clustering similar to what has been done for technologies and characteristics in this article. Figure 16 shows the various characteristics, technologies and enabling factors that build an SMS. It has also been discussed why some technologies, such as **data analytics** and **cloud manufacturing**, although having many common elements, are being considered separately.

From our discussion, we derived a comprehensive list of 27 characteristics and 38 technologies associated with SM in current literature. We propose that such characteristics become the aspiring "qualities of being" (QoBs) or smart features that current and future manufacturing systems should pursue in order to acquire a certain degree of smartness toward becoming an advanced "smart" manufacturing system. QoBs aim to act as the "smart features" that are necessary for considering a manufacturing system "smart" (see Table 5). Technologies will change, as they evolve with time, but the smart features will remain the same. Hence, only the characteristics have been defined and mentioned in Table 5.

For example, a CPS-based architecture that uses PLCs and makes decisions for energy management[95] should be based on technology clusters such as CPS, smart product/part/material, data analytics and energy saving/efficiency. Another example of how VR and AR can lead to sustainability, better training and knowledge is presented in Blümel.[96] This example case includes the clusters visual technology, energy saving/efficiency for the technology cluster and innovative education and training as the enabling factor cluster.

Such key characteristics and technologies are aimed, on one hand, to act as the capabilities to enable SM to comply with the six design principles of Industry 4.0 scenarios.[97] These principles being (1) *interoperability* as the ability of SMSs and technologies (e.g. machines, devices, sensors, systems and people) to connect and communicate with each other in the IoT, Services and People (IoTSP) (also known as the Internet of Everything (IoE)); (2) *virtualization* or *information transparency* as the ability of manufacturing information systems to create a digital/virtual copies of things in the physical world, which are created by linking sensor data with virtual models and simulation models; (3) *decentralization* as the ability of SMSs and technologies to make decisions on their own and to perform their tasks as autonomous as possible, including exceptions, interferences and/or conflicting goals' handling; (4) *real-time capability* as the ability to collect and analyze data and immediately provide the derived insights; (5) *service orientation* as the offering of services via the IoS and (6) *modularity* as the flexible adaptation of manufacturing systems (cf FMSs) to the changing requirements by replacing or expanding individual modules. Altogether, these key characteristics and technologies guide the design and engineering of SMSs that are Industry 4.0–enabled. Table 6 presents the SM characteristics and technologies associated with the Industry 4.0 design principles;[97] various manifestations corresponding to them are also mentioned.

However, the identified SM key characteristics and technologies should also be related to the 6Cs characteristics of CPSs and big data analytics[97] as core enabling technologies associated with the smartness attribute of manufacturing systems, including (1) *connectivity* with sensors and networks (e.g. IoT/IoS/IIoT), (2) *cloud* computing and data on-demand (e.g. cloud manufacturing), (3) *cyber* model and memory (e.g. CPSs), (4) *content/context* meaning and correlation (e.g. analytics), (5) *community* sharing and collaboration (e.g. intelligent control) and (6) *customization* through personalization and value (e.g. IT-based production management). In this way, SM will be enabled to provide useful insights to the shop-floor management to utilize data and information to increase the flexibility of manufacturing processes and respond rapidly to changes in demand at low cost to the SM enterprise. Table 7 presents the SM characteristics and technologies associated with the 6Cs characteristics of CPSs and big data analytics;[98] the various manifestations corresponding to them are also mentioned.

Conclusion and limitations

This article identified, discussed and clustered characteristics, technologies and enabling factors that might be used to define SM and SMSs and thus provide a foundation for a future comprehensive SM ontology. Overall, it was determined that there are five characteristics, namely, context awareness, modularity,

Table 5. Smart features for manufacturing system.

Sl no.	Qualities of being	Smart features
1	Digital presence	Being able to create digital or cyber-physical models of parts or the complete manufacturing system to develop a simulation environment for advanced planning, decision support and validation capability, before any action is implemented physically.
2	Modularity	Being able to create "economies of scale" within the manufacturing system.
3	Heterogeneity	Being able to create "economies of scope" within the manufacturing system.
4	Scalability	Being able to adjust (e.g. increase) production capacity through the manufacturing system reconfiguration with minimal cost and in minimal time.
5	Context awareness	Being able to automatically and in real-time collect manufacturing system data via a network of sensors (e.g. IoT), and subsequently conduct real-time processing (event or data-driven) to provide the proper information to the right people or system and the right time.
6	Autonomy	Being able to support (autonomous) reasoning, planning and decision-making via hardware, software, sensors and communication technology to increase a manufacturing system's productivity and flexibility.
7	Adaptability	Being able to manage unforeseen events during production as a manufacturing system. Adaptability may include flexibility and robustness features' capabilities.
8	Robustness	Being able to cope with problems during production as a manufacturing. Robustness can be achieved through redundancy.
9	Flexibility	Being able to produce different products on the same manufacturing system.
10	Fully automated	Being able to fully control by means of a computer system parts or the complete manufacturing system.
11	Asset self-awareness	Being able to sense a phenomenon or event within itself (the asset), such as its location, condition or availability within the manufacturing system.
12	Interoperability	Being able to allow communication through interfaces between the components/sub-systems of a manufacturing system, allowing it to work with or use parts of another components/sub-systems.
13	Networkability	Being able to allow information exchange and communication between the components/sub-systems of a manufacturing system.
14	Information appropriateness	Being able to acquire information from one or more sources within the manufacturing system components and sub-systems, store it and assure its quality, accessibility and understandability, as well as its provisioning to the right people or system and the right time.
15	Integrability	Being able to bring together different component sub-systems (e.g. machine tools, robots, computer systems, humans) of a manufacturing system into one integrated system and ensuring that all the sub-systems function together as a coordinated whole.
16	Sustainability	Being able to conduct all manufacturing processes and system operations with minimum environmental footprint (e.g. resource efficiency).
17	Compositionality	Being able to provide recombinant components within a manufacturing system that can be
18	Composability	selected and assembled in various combinations to satisfy specific production requirements.
19	Proactivity	Being able to anticipate (predict), by means of continuous situation-awareness capabilities, events (e.g. problems) in the production or manufacturing system components (e.g. machine tool) and react ahead of time (e.g. proactive maintenance).
20	Reliability	Being able to perform the required manufacturing processes and operations as a "reliable" manufacturing system under stated conditions, to achieve production objectives. Condition monitoring and defect diagnosis are enablers to improve the reliability of a manufacturing system.
21	Agility	Being able to respond to external changes (e.g. market changes) that affect production plans.
22	Responsiveness	Being able to provide a "quick response" to changes in production plans.
23	Accuracy	Being able to produce with minimal or zero-waste in all manufacturing processes and operations (e.g. lean manufacturing).
24	Reusability	Being able to use existing assets as they are or by modifying them in the manufacturing system in some form or other to reduce the introduction of new ones.
25	Decentralized	Being able to allow the components or sub-systems of a manufacturing system to operate on local information to accomplish global production goals.
26	Distributed	Being able to produce in dispersed manufacturing facilities that are coordinated using information and communication technology.
27	Resilience	Being able to tolerate large perturbations during production and still achieve production goals (e.g. in terms of product quality, delivery time, production cost).

IoT: Internet of Things.

heterogeneity, interoperability and compositionality; 11 technologies, namely, intelligent control, energy saving/efficiency, cyber security, CPS/CPPS, visual technology, IoT/IoS, cloud computing/cloud manufacturing, 3D printing/additive manufacturing, smart product/part/materials, data analytics and IT-based production management; as well as three enabling factors, namely, law and regulations, innovative education and training and data sharing systems, that are required in SM. These characteristics, technologies and enabling factors might also be used to classify a manufacturing system as smart. Additionally, these characteristics and technologies were matched with the design principles of Industry 4.0[97] and the key characteristics of CPSs and

Table 6. Design principles for SMS readiness for Industry 4.0 scenarios.

Sl no.	Industry 4.0 design principles	SM characteristics	SM-associated technologies	Selected manifestations
1	Interoperability	Interoperability Networkability Distributed Information appropriateness Integrability Sustainability	Cyber security Interface IT-based production management	Interoperability frameworks Interoperability standards Middleware Plug-and-play solutions IoE M2M
2	Virtualization	Context awareness Digital presence Asset self-awareness	Holograms VR AR CPS/CPPS Modeling Simulation CAM/CAD/CAx	Virtual organization Virtual factory Digital factory Digital manufacturing Digital services Digital twin Product avatar
3	Decentralization	Modularity Heterogeneity Autonomy Asset self-awareness Sustainability Compositionality Decentralized Distributed Resilience	Cyber-physical infrastructure Cloud computing/ cloud manufacturing 3D printing/additive manufacturing GIS	Cloud environments (public, private, hybrid) Local production (produce on-site) Rapid prototyping
4	Real-time capability	Context awareness Asset self-awareness Fully automated Sustainability Proactivity Reliability Agility Responsiveness Accuracy	Intelligence Intelligent control Energy saving/efficiency Real-time communication/data Big data Data analytics Predictive analytics Data visualization Forecasting Machine learning MES Operations planning Tracking and tracing Knowledge decision-making techniques SPC	Sensing enterprise Proactive enterprise Smart enterprise Smart factory Intelligent products Intelligent assets Intelligent services Intelligent maintenance systems
5	Service orientation	Modularity Interoperability Networkability Composability	Intelligence Intelligent control IoT/IoS/IIoT Smart sensors Smart products/parts RFID Smart materials	SOA SOC Software/platform/ infrastructure-as-a-service Servitization paradigm IoS Digital services IPSS
6	Modularity	Modularity Scalability Autonomy Adaptability Robustness Flexibility Sustainability Composability Reusability	Advanced manufacturing ERP SCM MES PLM CAM/CAD/CAx	Plug-and-produce paradigm Mass-customization paradigm

SM: smart manufacturing; IoE: Internet of Everything; M2M: machine-to-machine communication; VR: virtual reality; AR: augmented reality; CPS: cyber-physical system; CPPS: cyber-physical production system; CAM: computer-aided manufacturing; CAD: computer-aided design; CAx: computer-aided X; 3D: three-dimensional; GIS: Geographic Information Science; MES: manufacturing execution system; SPC: statistical process control; IoT: Internet of Things; IoS: Internet of Services; IIoT: Industrial Internet of Things; RFID: radio-frequency identification; SOA: service-oriented architecture; SOC: service-oriented computing; IPSS: industrial product-service system; ERP: enterprise resource planning; SCM: supply chain management; MES: manufacturing execution system; PLM: product lifecycle management.

Table 7. The 6Cs for smart manufacturing systems in cyber-physical environments.

Sl no.	6Cs	SM characteristics	SM-associated technologies	Selected manifestations
1	Connectivity	Interoperability Networkability Distributed Information appropriateness Integrability Sustainability Reliability Agility Decentralized Distributed Resilience	Cyber security Real-time communication/data IoT/IoS/IIoT RFID Machine learning Interfaces IT based on production management	Pervasive or ubiquitous computing AAA paradigm (anywhere, anytime, anybody/any type/any device) IT integration (vertical and horizontal integration) Mobile devices
2	Cloud	Interoperability Networkability Modularity Scalability Integrability Compositionality Composability Decentralized Distributed	Energy saving/efficiency Cloud computing/cloud manufacturing IT based on production management	Cloud-based applications Cloud manufacturing Distributed manufacturing
3	Cyber	Interoperability Networkability Context awareness Digital presence Asset self-awareness Integrability Compositionality Composability	Cyber security Holograms VR AR Cyber-physical infrastructure CPS/CPPS CAM/CAD/CAx IT based on production management	Visual technologies Sensor networks Internet communication Infrastructure Intelligent, real-time processing and event management Big data and data provisioning Embedded software for logic Automated operations
4	Content/context	Context awareness Asset self-awareness Fully automated Information appropriateness Sustainability Proactivity Responsiveness Accuracy	Intelligence Intelligent control Big data Smart sensors Smart products/parts Data analytics Predictive analytics Data visualization Modeling Simulation Forecasting Machine learning Operation planning Tracking and tracing Knowledge decision-making techniques SPC	Sensor networks IoT platforms Data analytics Data management
5	Community	Modularity Heterogeneity Autonomy Robustness Fully automated Integrability Compositionality Composability Decentralized Distributed Resilience	IoT/IoS/IIoT Smart sensors Smart products/parts GIS ERP RFID Machine learning SCM MES PLM Smart materials CAM/CAD/CAx	Collaborative virtual factory Social networks Grid computing Distributed manufacturing IIoT Sharing economy

(continued)

Table 7. Continued

Sl no.	6Cs	SM characteristics	SM-associated technologies	Selected manifestations
6	Customization	Modularity Heterogeneity Adaptability Flexibility Integrability Compositionality Composability Reusability	Advanced manufacturing 3D printing/additive manufacturing Smart products/parts ERP Machine learning SCM MES PLM CAM/CAD/CAx	Flexible manufacturing systems Reconfigurable manufacturing systems On-demand manufacturing Customer-centric production

SM: smart manufacturing; IoT: Internet of Things; IoS: Internet of Services; IIoT: Industrial Internet of Things; RFID: radio-frequency identification; VR: virtual reality; AR: augmented reality; CPS: cyber-physical system; CPPS: cyber-physical production system; CAM: computer-aided manufacturing; CAD: computer-aided design; CAx: computer-aided X; SPC: statistical process control; GIS: Geographic Information Science; ERP: enterprise resource planning; SCM: supply chain management; MES: manufacturing execution system; PLM: product lifecycle management; 3D: three-dimensional.

big data analytics.[98] It was found that all the identified characteristics and technologies match with the design principles of Industry 4.0 and CPS.

In a next step, a very similar approach could be used to classify other popular initiatives such as smart factory, intelligent manufacturing and distributive manufacturing. Based on this clarification, a mapping of the different initiatives and a "degree of similarity" might be derived to identify overlaps and areas where these initiatives complement each other.

In this article, we can also observe that there are a smaller number of clustered characteristics compared to the number of clustered technologies. One possible explanation for this occurrence is that the technologies need certain characteristics as input and it would have been redundant to consider such characteristics separately. For example, scalability, flexibility, adaptability, robustness, autonomy, fully automated and proactivity were clustered in the technology intelligent control. However, we do not have technology/technologies clustered into a characteristic as they depend on later. Furthermore, it was also discussed why advanced manufacturing is a manufacturing system itself and should not be considered as a part of technologies.

Another finding this article addresses is that some of the technologies such as GIS, smart materials, tracking and tracing could be considered as part of both data analytics and smart parts/products/materials. It is the application of the technology which determines the cluster it will belong to. Therefore, the application will vary with the objective of SM.

The resultant list is to be understood as a first step in defining a comprehensive list of commonly agreed upon SM characteristics, technologies and enabling factors. The authors encourage industry and academic experts to provide feedback to further develop this list. This can lead to additional expansion or reduction in the current list. A similar development is expected if an increasing amount of new SM literature, including applications, is published in the future containing additional or more clearly defined characteristics, technologies and enabling factors.

There are several limitations in this article, which need to be mentioned. First, when the identified articles were thoroughly read to prepare a list of characteristics, technologies and enabling factors, it was found that many articles mention SM only once in the title and/or in the keywords. This might lead to the interpretation that the term is strongly associated with positive goals (e.g. federal funding opportunities, "hot topic") and authors would incorporate SM in the title to be more visible. It has to be observed if this changes once SM is more established and the definition is broadly disseminated among academics and industry.

Furthermore, while extracting the characteristics, technologies and enabling factors from literature sources where they were not directly mentioned and classified as such, the subjective perspective of the authors plays a part in the decision of choosing either technology or characteristic as the defining element. These characteristics and definitions are from a small set of research and there might be some others, which were not reviewed. The clusters in this work are based on the knowledge, expertise, experience and perspective of the authors. Some of the characteristics and technologies were listed in the literature, but definitions were not explicitly provided. Therefore, these characteristics and technologies were defined from other articles and the authors' knowledge. The authors tried to increase the transparency of the clustering by explaining the reasoning of the decisions. Another limitation of this article is that there was only one article covering Industry 4.0 and CPS that was considered by the authors to find the design principles of Industry 4.0 and characteristics of CPS. However, this article should be considered as a first step toward a commonly accepted list of defining characteristics and technologies for SM that eventually leads to a comprehensive SM ontology. Readers are actively encouraged to provide feedback and challenge the selection.

Acknowledgements

The authors would like to express their gratitude to the members of IFIP WG 5.1 and 5.7 as well as the SMLC for their valuable input and encouragement at the different stages of this study. Furthermore, the authors thank the participants of the NIST Smart Manufacturing workshop 2016 and 2017 for the inspiration. Finally, the authors would like to thank the reviewers for their valuable comments that helped to significantly improve the article. The article is an enhanced and extended version of the following publication "Mittal, S., Khan, M. & Wuest, T. (2016). Smart Manufacturing: Characteristics and Technologies. 13th International Conference on Product Lifecycle Management (PLM) 2016, July 11–13., 2016, Columbia, SC, USA."

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the J. Wayne & Kathy Richards Faculty Fellowship in Engineering at WVU.

References

1. Davis J, Edgar T, Graybill R, et al. Smart manufacturing. *Annu Rev Chem Biomol Eng* 2015; 6: 141–160.
2. Lightfoot HW, Baines T and Smart P. Examining the information and communication technologies enabling servitized manufacture. *Proc IMechE, Part B: J Engineering Manufacture* 2011; 225: 1964–1968.
3. Esmaeilian B, Behdad S and Wang B. The evolution and future of manufacturing: a review. *J Manuf Syst* 2016; 39: 79–100.
4. Energy-efficient buildings: multi-annual roadmap for the contractual PPP under Horizon 2020. Brussels: European Commission Directorate-General for Research & Innovation, 2013, http://www.buildup.eu/en/practices/publications/energy-efficient-buildings-multi-annual-roadmap-contractual-ppp-under-horiz-0
5. Jung K, Kulvatunyou B, Choi S, et al. An overview of a smart manufacturing system readiness assessment. In: *Proceedings of the international conference on advances in production management systems*, Iguassu Falls, Brazil, 3–7 September 2016, pp.705–712. Berlin: Springer.
6. Teramoto K, Wu D, Ota K, et al. A framework of accuracy assured machining for smart manufacturing. *Mem Muroran Inst Tech* 2016; 65: 35–39.
7. Anderson A. Report to the President on ensuring American leadership in advanced manufacturing. *Executive Office of the President*, 2011, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf
8. Tao F, Cheng Y, Zhang L, et al. Advanced manufacturing systems: socialization characteristics and trends. *J Intell Manuf* 2015; 28: 1–6.
9. Kim DB, Denno PO and Jones AT. A model-based approach to refine process parameters in smart manufacturing. *Concurrent Eng* 2015; 23: 365–376.
10. Kühnle H and Bitsch G. *Foundations & principles of distributed manufacturing*. Berlin: Springer, 2015, pp.55–70.
11. Strozzi F, Colicchia C, Creazza A, et al. Literature review on the "Smart Factory" concept using bibliometric tools. *Int J Prod Res* 2017; 11: 1–20.
12. Thoben KD, Wiesner S and Wuest T. "Industrie 4.0" and smart manufacturing—a review of research issues and application examples. *Int J Autom Technol* 2017; 11: 4–16.
13. Harispe S, Ranwez S, Janaqi S, et al. Semantic similarity from natural language and ontology analysis. *Synth Lect Hum Lang Technol* 2015; 8: 1–254.
14. Rachuri S. Smart manufacturing systems design and analysis. *National Institute of Standards and Technology*, 2015, https://www.nist.gov/programs-projects/smart-manufacturing-systems-design-and-analysis-program
15. Trombley D and Rogers E. *Benefits and barriers of smart manufacturing*. *Energy systems laboratory*. College Station, TX: Texas A&M University, 2014.
16. Qu S, Jian R, Chu T, et al. Computational reasoning and learning for smart manufacturing under realistic conditions. In: *Proceedings of the international conference on behavioral, economic, and socio-cultural computing*, Shanghai, China, 30 October 2014, pp.1–8. New York: IEEE.
17. Jung K, Morris K, Lyons KW, et al. *Performance challenges identification method for smart manufacturing systems*. Report no. 8108, 27 November 2015. Gaithersburg, MD: National Institute of Standards and Technology.
18. Lee YT, Kumaraguru S, Hatim Q, et al. A classification scheme for smart manufacturing systems' performance metrics. *ASTM J Smart Sustain Manuf* 2017; 1: 52–74.
19. Kusiak A. A four-part plan for smart manufacturing. *ISE Mag* 2017; 49: 43–47.
20. Park J and Lee J. Presentation on Korea smart factory program. In: *Proceedings of the international conference on advances in production management systems*, Tokyo, Japan, 5–9 September 2015. Berlin: Springer.
21. Davis J. Cyberinfrastructure in chemical and biological process systems: impact and directions. NSF workshop report, Arlington, VA, https://smartmanufacturingcoalition.org/sites/default/files/the_norma_language_application_to_solution_of_strong_nonequilibrium_transfer.pdf (2006, accessed 29 March 2017).
22. Park HS and Tran NH. Autonomy for smart manufacturing. *J Korean Soc Precis Eng* 2014; 31: 287–295.
23. Smart Process Manufacturing Engineering Virtual Organization Steering Committee. Smart process manufacturing: an operations and technology roadmap, https://smartmanufacturingcoalition.org/sites/default/files/spm__an_operations_and_technology_roadmap.pdf (2009, accessed 29 March 2017).
24. Rathinasabapathy R, Elsass MJ, Josephson JR, et al. A smart manufacturing methodology for real time chemical process diagnosis using causal link assessment. *AIChE J* 2016; 62: 3420–3431.
25. Kibira D, Morris K and Kumaraguru S. Methods and tools for performance assurance of smart manufacturing systems. *J Nat Inst Stand Technol* 2015; 8099.

26. Papazoglou MP, Van Den Heuvel WJ and Mascolo JE. Reference architecture and knowledge-based structures for smart manufacturing networks. *IEEE Softw* 2015; 32: 61–69.
27. Lu Y, Morris KC and Frechette S. Standards landscape and directions for smart manufacturing systems. In: *Proceedings of the IEEE international conference on automation science and engineering*, Gothenburg, 24 August 2015, pp.998–1005. New York: IEEE.
28. Kusiak A. Smart manufacturing. *Int J Prod Res* 2017; 14: 1–10.
29. Cheng K. Keynote presentation—2: smart tooling, smart machines and smart manufacturing: working towards the Industry 4.0 and beyond. In: *Proceedings of the 21st international conference on automation and computing*, Glasgow, Scotland, 11 September 2015, pp.11–12. New York: IEEE.
30. Kang HS, Lee JY, Choi S, et al. Smart manufacturing: past research, present findings, and future directions. *Int J Precis Eng Manuf* 2016; 3: 111–128.
31. Malik JA. US expects energy savings through smart manufacturing. *MRS Bull* 2016; 41: 10–11.
32. Choi S, Jung K and Do Noh S. Virtual reality applications in manufacturing industries: past research, present findings, and future directions. *Concurr Eng* 2015; 23: 40–63.
33. Korambath P, Wang J, Kumar A, et al. A smart manufacturing use case: furnace temperature balancing in steam methane reforming process via Kepler workflows. *Procedia Comput Sci* 2016; 80: 680–689.
34. Leitão P, Colombo AW and Karnouskos S. Industrial automation based on cyber-physical systems technologies: prototype implementations and challenges. *Comput Ind* 2016; 81: 11–25.
35. Kulvatunyou B, Ivezic N, Morris KC, et al. Drilling down on smart manufacturing–enabling composable apps. *Manuf Lett* 2016; 10: 14–17.
36. Lao L, Ellis M and Christofides PD. Smart manufacturing: handling preventive actuator maintenance and economics using model predictive control. *AlChE J* 2014; 60: 2179–2196.
37. Shin SJ, Woo J and Rachuri S. Predictive analytics model for power consumption in manufacturing. *Procedia CIRP* 2014; 15: 153–158.
38. Schabus S and Scholz J. Geographic Information Science and technology as key approach to unveil the potential of Industry 4.0: how location and time can support smart manufacturing. In: *Proceedings of the 12th international conference on informatics in control, automation and robotics*, Colmar, 21 July 2015, pp.463–470. New York: IEEE.
39. Kusiak A. Smart manufacturing must embrace big data. *Nature* 2017; 544: 23–25.
40. Shao G, Shin SJ and Jain S. Data analytics using simulation for smart manufacturing. In: *Proceedings of the winter simulation conference*, Savannah, GA, 7 December 2014, pp.2192–2203. New York: IEEE.
41. Bryner M. Smart manufacturing: the next revolution. *Chem Eng Prog* 2012; 108: 4–12.
42. Choi S, Kim BH and Do Noh S. A diagnosis and evaluation method for strategic planning and systematic design of a virtual factory in smart manufacturing systems. *Int J Precis Eng Manuf* 2015; 16: 1107–1115.
43. Lee I and Lee K. The Internet of Things (IoT): applications, investments, and challenges for enterprises. *Bus Horizons* 2015; 58: 431–440.
44. Nezhad MN. Smart manufacturing systems: real-time data analytics. *Advances in Embedded Interactive Systems*, Technical Report. 2016; 4: 20–26.
45. Wu D, Jennings C, Terpenny J, et al. A comparative study on machine learning algorithms for smart manufacturing: tool wear prediction using random forests. *J Manuf Sci Eng* 2017; 139: 071018.
46. Sinha S. Advanced/smart manufacturing: from nanoscale to megascale. *IEEE Potentials* 2016; 35: 7–8.
47. Bostelman R, Falco J, Shah M, et al. Dynamic metrology performance measurement of a six degrees-of-freedom tracking system used in smart manufacturing. In: *Proceedings of the Autonomous industrial vehicles: from the laboratory to the factory floor*, 2016. West Conshohocken, PA: ASTM International. https://www.astm.org/DIGITAL_LIBRARY/STP/PAGES/STP159420150056.htm, DOI: 10.1520/STP159420150056.
48. Shafiq SI, Sanin C, Szczerbicki E, et al. Decisional DNA based conceptual framework for smart manufacturing. In: *Proceedings of the international conference on information systems architecture and technology*, Karpacz, 20–22 September 2015, pp.79–88. Berlin: Springer.
49. Stephen JE. A policymaker's guide to smart manufacturing. Report, Information Technology & Innovation Foundation, Washington, DC, November 2016.
50. Feeney AB, Frechette SP and Srinivasan V. A portrait of an ISO STEP tolerancing standard as an enabler of smart manufacturing systems. *J Comput Inf Sci Eng* 2015; 15: 021001.
51. Hudson S. Smart manufacturing and smarter talent acquisition and development: extending Alcoa's talent pipeline into communities. *People Strategy* 2014; 37: 40–46.
52. Kulvatunyou B, Ivezic N and Srinivasan V. On architecting and composing engineering information services to enable smart manufacturing. *J Comput Inf Sci Eng* 2016; 16: 031002.
53. Abowd GD, Ebling M, Hung G, et al. Context-aware computing [guest editors' intro.]. *IEEE Pervas Comput* 2002; 1: 22–23.
54. Zuehlke D. Smart factory—towards a factory-of-things. *Annu Rev Control* 2010; 34: 129–138.
55. De Weck OL, Ross AM and Rhodes DH. Investigating relationships and semantic sets amongst system lifecycle properties (ilities). In: *Proceedings of the third international engineering systems symposium*, 18–20 June 2012. Delft: Delft University of Technology.
56. Stengel R. Robotics and intelligent systems, https://www.princeton.edu/~stengel/MAE345Lecture1.pdf (2015, accessed 29 March 2017).
57. Báez-González P, Alejandro J, Carlini MA, et al. Day-ahead economic optimization of energy use in an olive mill. *Control Eng Pract* 2016; 54: 91–103.
58. Matsushima K, Nakahara S, Arima Y, et al. Computer holography: 3D digital art based on high-definition CGH. *J Phys Conf Ser* 2013; 415: 12–53.
59. Steuer J. Defining virtual reality: dimensions determining telepresence. *J Commun* 1992; 42: 73–93.
60. Earnshaw RA. *Virtual reality systems*. Cambridge, MA: Academic press, 2014.
61. Azuma RT. A survey of augmented reality. *Teleoperators Virtual Environ* 1997; 6: 355–385.

62. Yu C, Xu X and Lu Y. Computer-integrated manufacturing, cyber-physical systems and cloud manufacturing—concepts and relationships. *Manuf Lett* 2015; 6: 5–9.
63. Ghahramani Z. Probabilistic machine learning and artificial intelligence. *Nature* 2015; 521: 452–459.
64. Waller MA and Fawcett SE. Data science, predictive analytics, and big data: a revolution that will transform supply chain design and management. *J Bus Logist* 2013; 34: 77–84.
65. Fan W and Bifet A. Mining big data: current status, and forecast to the future. *ACM SIGKDD Explor Newsletter* 2013; 14: 1–5.
66. Chai J, Liu JN and Ngai EW. Application of decision-making techniques in supplier selection: a systematic review of literature. *Expert Syst Appl* 2013; 40: 3872–3885.
67. Lee EA. Cyber physical systems: design challenges. In: *Proceedings of the 11th IEEE international symposium on object and component-oriented real-time distributed computing*, Orlando, FL, 5–7 May 2008. New York: IEEE.
68. Monostori L Cyber-physical production systems: roots, expectations and R&D challenges. *Procedia CIRP* 2014; 17: 9–13.
69. Wang M, Zhong RY, Dai Q, et al. A MPN-based scheduling model for IoT-enabled hybrid flow shop manufacturing. *Adv Eng Inf* 2016; 30: 728–736.
70. Alberti AM and Singh D. Internet of things: perspectives, challenges and opportunities. In: *Proceedings of the international workshop on telecommunications* (IWT 2013), INATEL, Brazil, 6–9 May 2013.
71. Klötzer C and Pflaum A. Cyber-physical systems as the technical foundation for problem solutions in manufacturing, logistics and supply chain management. In: *Proceedings of the 5th international conference on internet of things*, Seoul, Korea, 26–28 October 2015. New York: IEEE.
72. Ning H and Wang Z. Future internet of things architecture: like mankind neural system or social organization framework? *IEEE Commun Lett* 2011; 15: 461–463.
73. Tao F, Zhang L, Venkatesh VC, et al. A computing and service-oriented manufacturing model. *Proc IMechE, Part B: J Engineering Manufacture* 2011; 225: 1969–1976.
74. Paunescu D, Stark WJ and Grass RN. Particles with an identity: tracking and tracing in commodity products. *Powder Technol* 2016; 291: 344–350.
75. Kumar A, Baldea M, Edgar TF, et al. Smart manufacturing approach for efficient operation of industrial steam-methane reformers. *Indus Eng Chem Res* 2015; 54: 4360–4370.
76. Bindel A, Rosamond E, Conway P, et al. Product life cycle information management in the electronics supply chain. *Proc IMechE, Part B: J Engineering Manufacture* 2012; 226: 1388–1400.
77. Bindel A, Conway PP and West AA. Information structure required for life-cycle monitoring of electronic products. *Proc IMechE, Part B: J Engineering Manufacture* 2012; 226: 1612–1627.
78. Yuan L, Guo Y, Wei F, et al. Radio frequency identification–enabled monitoring and evaluating in the discrete manufacturing process. *Proc IMechE, Part B: J Engineering Manufacture*. Epub ahead of print 29 June 2017. DOI: 10.1177/0954405415620986.
79. Rade DA and Steffen V. Introduction to smart materials and structures. In: Junior L, Steffen V and Savi V (eds) *Dynamics of smart systems and structures*. Berlin: Springer, 2016, pp.121–134
80. Khan MA, Rozati GL and Wuest T. Sensor triggered replacement of spare parts: customer service process innovation. In: *Proceedings of the IFIP international conference international conference on advances in production management systems*, Iguassu Falls, Brazil, 3–7 September 2016. Berlin: Springer.
81. Spaggiari A, Castagnetti D, Golinelli N, et al. Smart materials: properties, design and mechatronic applications. *Proc IMechE, Part L: J Materials: Design Applications*. Epub ahead of print 12 December 2016. DOI: 10.1177/1464420716673671.
82. Nettsträter A, Geißen T, Witthaut M, et al. Logistics software systems and functions: an overview of ERP, WMS, TMS and SCM systems. In: Hompel M, Rehof J and Wolf O (eds) *Cloud computing for logistics*. Berlin: Springer, 2015, pp.1–11.
83. Chopra S and Meindl P. Supply chain management. Strategy, planning & operation. In: Boersch H and Eschen C (eds) *Das Summa Summarum des Management*. Berlin: Springer, 2007, pp.265–275.
84. Blanc P, Demongodin I and Castagna P. A holonic approach for manufacturing execution system design: an industrial application. *Eng Appl Artif Intell* 2008; 211: 315–330.
85. Stark J. Product lifecycle management. In: Saaksvuori A and Immonen A (eds) *Product lifecycle management*. Berlin: Springer, 2015, pp.1–29.
86. Manafi D, Nategh MJ and Parvaz H. Extracting the manufacturing information of machining features for computer-aided process planning systems. *Proc IMechE, Part B: J Engineering Manufacture* 2016; 15: 1–12.
87. Kocaoğlu B, Gülsün B and Tanyaş M. A SCOR based approach for measuring a benchmarkable supply chain performance. *J Intell Manuf* 2013; 24: 113–132.
88. Zuñiga R, Seifert M and Thoben KD. Study on the application of DCOR and SCOR models for the sourcing process in the mineral raw material industry supply chain. In: Kreowski H, Scholz-Reiter B and Thoben KD (eds) *Dynamics in logistics*. Berlin; Heidelberg: Springer, 2013, pp.211–220.
89. Robles T, Alcarria R, Martın D, et al. An IoT based reference architecture for smart water management processes. *J Wirel Mob Netw Ubiquit Comput Dependable Appl* 2015; 6: 4–23.
90. Chryssolouris G, Mavrikios D, Papakostas N, et al. Digital manufacturing: history, perspectives, and outlook. *Proc IMechE, Part B: J Engineering Manufacture* 2009; 223: 451–462.
91. Lu Y, Morris KC and Frechette S. *Current standards landscape for smart manufacturing systems*. Report no. 8107, 23 February 2016. Gaithersburg, MD: National Institute of Standards and Technology.
92. Ma R and Ho YS. Comparison of environmental laws publications in Science Citation Index Expanded and Social Science Index: a bibliometric analysis. *Scientometrics* 2016; 1–3.
93. Pavlovic A and Fragassa C. Analysis of flexible barriers used as safety protection in woodworking. *Int J Qual Res* 2016; 10: 71–88.
94. Bruton K, O'Donovan P, McGregor A, et al. Design and development of a software tool to assist ISO 50001 implementation in the manufacturing sector. *Proc IMechE,*

Part B: J Engineering Manufacture. Epub ahead of print 26 December 2016. DOI: 10.1177/0954405416683427.

95. Bruton K, Walsh BP, óg Cusack D, et al. Enabling effective operational decision making on a combined heat and power system using the 5C architecture. *Procedia CIRP* 2016; 55: 296–301.
96. Blümel E. Global challenges and innovative technologies geared toward new markets: prospects for virtual and augmented reality. *Procedia Comput Sci* 2013; 25: 4–13.
97. Hermann M, Pentek T and Otto B. Design principles for Industrie 4.0 scenarios. In: *Proceedings of the 49th Hawaii international conference on system sciences*, Kauai, HI, 5 January 2016, pp.3928–3937. New York: IEEE.
98. Lee J, Bagheri B and Kao HA. Recent advances and trends of cyber-physical systems and big data analytics in industrial informatics. In: *Proceedings of the international conference on industrial informatics*, Porto Alegre, Brazil, 27–30 July 2014. New York: IEEE.