The fit of Industry 4.0 applications in manufacturing logistics – a multiple case study

Jo Wessel Strandhagen, Erlend Alfnes, Jan Ola Strandhagen, Logan Reed Vallandingham
Department of Mechanical and Industrial Engineering
Norwegian University of Science and Technology
Trondheim, Norway
e-mail: jo.w.strandhagen@ntnu.no
ORCID 0000-0002-2454-4294

Abstract The fourth industrial revolution, Industry 4.0, is expected to cause disruptive changes in industrial production. It is driven by rapid technological developments and the need for manufacturing companies to make oneself independent of high labor costs. Industry 4.0 concerns several aspects of industrial production, including manufacturing logistics, business models and products and services. The applications of Industry 4.0 have been vastly outlined. However, the fit of Industry 4.0 applications in different production environments is not clear. The purpose of this paper is to identify and investigate the Industry 4.0 technologies that are applicable to manufacturing logistics, and how the production environment influence the applicability of these technologies. This is done through a multiple case study of four Norwegian manufacturing companies. The findings from the study indicate that the applicability of Industry 4.0 in manufacturing logistics is dependent on the production environment. Companies with a low degree of production repetitiveness see less potential in applying Industry 4.0 technologies in manufacturing logistics, while companies with a highly repetitive production see a higher potential.

Keywords—Industry 4.0, Manufacturing logistics, Production planning and control, Production environment

1. Introduction

The fourth industrial revolution, Industry 4.0, is expected to cause disruptive changes in industrial production. Originating from the German strategic initiative Industrie 4.0 [1], it is now on the agenda in several European countries and in the US and Asia. It is built around rapidly developing technologies and concepts, e.g. the Internet of Things (IoT), and is expected to lead to a paradigm shift in industrial production. To remain competitive, Norwegian manufacturers and manufacturers in countries where labor costs are high should explore the concept of Industry 4.0 to enable exploitation of the specific benefits it can offer in terms of new solutions for production and logistics in industrial production.

Industry 4.0 is a broad term, used within several different fields of study, and its scope covers the entirety of industrial manufacturing. This can make it difficult to grasp, for both academia and practitioners, thus breaking it down and investigating it in the context of manufacturing logistics will make it more conceivable.

In the context of this paper, "manufacturing logistics" concerns the planning, control and configuration of logistics flow in a manufacturing company. The terms "manufacturing" and "production" are in this paper used as two interchangeable terms. How manufacturing logistics should be handled is dependent on the company's production environment [2, 3]. The production environment is here considered as the set of variables that describes the market related, product related and production process related characteristic features of a company. Industry 4.0 will have implications for industrial processes and value creation [1], and it includes several aspects relevant for manufacturing logistics. This leads to the hypothesis that the applicability of Industry 4.0 technologies in manufacturing logistics is dependent on the company's production environment. If Industry 4.0 is to improve manufacturing logistics performance, there are reasons to believe that the production environment will have a major impact on what aspects of Industry 4.0 should be approached for a specific company and how these should be approached. Moreover, recent years' research papers, governmental reports and strategy plans, media reports and popular science articles outline numerous applications of Industry 4.0. However, it is not well documented which applications will fit in which production environments. Thus, this paper sets out to investigate the fit of Industry 4.0 applications in manufacturing logistics when considering the characteristics of companies' production environments.

Two research questions have been formulated:

1) What are key applications of Industry 4.0 technology in the context of manufacturing logistics?

2) How is the applicability of these technologies affected by the production environment?

Through answering these research questions this paper aims to contribute to the existing theory on production environments, by investigating the relationship between applications of Industry 4.0 technology and production environments. The main contributions include the identification and classification of Industry 4.0 technologies for manufacturing logistics, an empirical analysis of the case companies and their production environment, as well as a proposition regarding the fit of Industry 4.0 applications in manufacturing logistics.

This paper is an extended version of "Importance of production environments when applying Industry 4.0 to production logistics – a multiple case study", presented at the 6th International Workshop of Advanced Manufacturing and Automation (IWAMA 2016). The rest of the paper is structured as follows. Sections 2, 3 and 4 will cover the theoretical background of relevant topics. Further, the methodology used in conducting the case studies is presented in section 5. A presentation of the case companies and findings from the case studies are provided in section 6, followed by a discussion of the findings in section 7. Conclusion, limitations and further research are provided in section 8.

2. What is the Industry 4.0 concept

Industry 4.0 can be described as an umbrella term, referring to a range of current concepts and touching several disciplines within industry [4]. The key drivers for this fourth industrial revolution can be divided in two aspects. The first is the combination of rapidly advancing technological developments of today, including Internet of Things (IoT), Internet of Services (IoS), Cyber-Physical Systems (CPS) smart objects and big data. Such technologies may result in a paradigm shift in industrial production [4], and this can be described as a technology push. The second aspect is the demand from manufacturing companies, especially in countries with high cost levels, to make oneself independent of high labor costs by exploiting new technology. Businesses will seek new ways of offering their products and services, and even new business models will emerge [1]. Hermann et al. [5] provides the following definition of Industry 4.0:

"Industry 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world, and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real-time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain."

2.1. Three types of integration

As described by Kagermann et al. [1], Wang et al. [6] and Brettel et al. [7] Industry 4.0 consists of three main features. These are three types of integration, which are expected to be the reality in future production networks. They are introduced in the following three paragraphs.

Vertical integration concerns the integration of various IT systems at the different hierarchical levels inside a factory [1]. Wang et al. [6] emphasizes the essentiality of vertically integrating the levels of the automation pyramid, from sensors and actuators on the shop floor, up through the Manufacturing Execution System (MES) and further up to the Enterprise Resource Planning (ERP) level. This will enable a flexible and reconfigurable manufacturing system [6, 7]. Such a vertical integration, with expanded utilization of planning tools, software and IT and digitalization of manufacturing has been stated as a requirement to ensure continued competitiveness for European manufacturing industry [8].

Horizontal integration through value networks will facilitate inter-corporation collaboration where material flow fluently among these corporations [6]. This integration describes the cross-company and company-internal intelligent cross-linking and digitalization of value creation modules [9]. Brettel et al. [7] points to the trend of decreasing depth of added value within one factory as an enabling factor for introducing Collaborative Manufacturing and Collaborative Development Environments. These are concepts where companies organize in networks in order to exploit fully the core competencies of every manufacturer within the network [10].

End-to-end engineering integration across the entire value chain will support the increasing requirements regarding product customization [6]. It includes cross-linking of stakeholders, products and equipment along the product life cycle, from raw material acquisition to end of life [9]. Brettel et al. [7] argue that value added services will become leverage opportunities to ensure a strong competitive position.

2.2. Components of Industry 4.0

Kagermann et al. [1] and Hermann et al. [5] identifies three components of Industry 4.0. These are Cyber-Physical Systems (CPS), Internet of Things (IoT) and Smart Factory. These will be described in the following three sub-sections.

2.2.1. Cyber-Physical Systems (CPS)

The fourth industrial revolution builds upon the implementation of Cyber-Physical Systems (CPS), which feature end-to-end ICT-based integration [1]. Lee [11] describes CPS as integrations of computation and physical processes, with embedded computers and networks monitoring and controlling physical processes. It can be considered as the merge between the physical and digital world [4]. In the manufacturing context, CPS comprise smart machines and production facilities that are capable of autonomously exchanging information, triggering actions and controlling each other independently [1]. Lee et al. [12] describes the two main functional components of a CPS:

- The advanced connectivity that ensures real-time acquisition of data from the physical world and information from the cyber space.
- Intelligent data management, analytics and computational capability that constructs the cyber space.

Hermann et al. [5] defines three characterizing phases in the development of CPS, listed below:

- Identification technologies (e.g., RFID)
- Sensors and actuators with a limited range of functions
- Multiple sensors and actuators, storing and analysis of data, and network compatibility.

2.2.2. Internet of Things (IoT)

According to [1] the Internet of Things (IoT) (and the Internet of Services (IoS)) are what is driving the fourth industrial revolution as ”The Internet of Things and Services makes it possible to create networks incorporating the entire manufacturing process that converts factories into a smart environment” [1]. As mentioned, the term Internet of Things is sometimes used for the fourth industrial revolution. Here, however, it is viewed as one of the four key components of Industry 4.0, as identified by Hermann et al. [5]. By the introduction of the Internet protocol IPv6, there are now enough available addresses to uniquely identify and network resources, information, objects and people, creating the IoT and IoS [1].

Hermann et al. [5] defines the IoT as ”a network in which CPS cooperate with each other through unique addressing schemas. Slack et al. [13] describes it as a combination of RFID chips, sensors and Internet protocols that allows networking of the location and state of physical objects. As ”things” and ”objects” can be understood as CPS [5], the IoT and CPS are closely linked components of Industry 4.0. Future internet technology will enhance the performance of cyber-physical systems [14]. The possibility to give a unique identification to every physical object will enable objects to be networked in the Internet of Things and tracked, which makes the object an information carrier [14].

Slack et al. [13] further elaborates on the IoT’s implications for operations management. The IoT will enable linking and networking of data from products, equipment and environment, enhancing information and enabling more sophisticated analysis [13]. Specifically, Slack et al. [13] addresses the knowledge of where things are, what is happening and what to do in an operations management context, as such knowledge can provide useful decision support. The IoT will enable gathering of this knowledge. Moreover, Slack et al. [13] emphasizes that the IoT will enhance monitoring and data collection, improving process control significantly within a production facility.

2.2.3. Smart Factory

Smart Factories is the third component of Industry 4.0, as described by Hermann et al. [5], which defines it as a factory where CPS communicate over the IoT, assisting humans and machines in task execution. It enables the collection, distribution and access of manufacturing relevant information in real-time [15]. Radziwon et al. [16] gives a more comprehensive definition of the term, saying: “A Smart Factory is a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising on a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity. This special solution could on the one hand be related to automation, understood as a combination of software, hardware and/or mechanics, which should lead to optimization of manufacturing resulting in reduction of unnecessary labour and waste of resource. On the other hand, it could be seen in a perspective of collaboration between different industrial and nonindustrial partners, where the smartness comes from forming a dynamic organization." This last definition gives a more general view on the Smart Factory concept, where the word "smart" characterizes objects that are enhanced by additional features increasing its abilities. Although the definition does not explicitly say anything about IoT or CPS, the words "software", "hardware" and "mechanics" are included, making the definition relatable to the other components of Industry 4.0 described earlier.

"Digital factory" is also used when describing the Smart Factory concept in relation to Industry 4.0 [4]. Yoon et al. [17] uses the term "Smart Factory" interchangeably with "Ubiquitous Factory", and defines it as "a factory system in which autonomous and sustainable production takes place by gathering, exchanging and using information transparently anywhere, anytime with networked interaction between man, machine, materials and systems, based on ubiquitous technology and manufacturing technology". "Smart Factory" can thus be considered a concept within the scope of Industry 4.0. Based on the preceding descriptions and definitions one can say that the Smart Factory is a factory where the other components of Industry 4.0 are combined and put in the context of production.

Having described the main features and key components of Industry 4.0 the next section will concern how these can be related to manufacturing logistics.

3. Industry 4.0 applications for Manufacturing logistics

Through a literature study, various applications of Industry 4.0 technologies in manufacturing logistics have been identified and placed in four groups (see Table 1). The groups, and the applications listed within each, are described in the following paragraphs.

Table 1 Industry 4.0 technologies for manufacturing logistics.

Decision support and decision-making	Identification and interconnectivity	Seamless information flow	Automation, robots and New production technology
Artificial intelligence	Sensors	Real-time control	Industrial robots
Big data analytics	Auto ID	Integration of IT systems	3D printing
Augmented and virtual reality	Networking technology	Cloud computing	Automatic Guided Vehicles

3.1. Decision support and decision-making

New technology within Industry 4.0 has the potential to greatly enhance decision support and provide more automated decision-making. The new possibilities to collect and analyze data from products and processes effectively can give great benefits for manufacturing logistics, as managers can base decisions on what is actually happening on the shop floor of a production facility. Moreover, this can allow automating decision-making, compared to traditional ERP systems, which traditionally only provides decision support. Industry 4.0 technologies also promise the introduction of artificial intelligence and augmented and virtual reality in manufacturing, providing a new way of decision support and decision-making.

Artificial intelligence. The application of artificial intelligence to production and logistics is seen as a natural step, and can assist in creating systems that make decisions and carry out actions based on the current environment [18]. Within the context of Industry 4.0, massive amounts of data can be gathered where equipment and products will be able to act alone without the intervention of humans. Applications of artificial intelligence in smart factories have been demonstrated which have had a large impact on both productivity and quality of resulting products [19].

Big data analytics. The collection and analysis of production relevant data is a key enabler of efficient decision-making [13]. Collecting and analyzing information enables managers to base decisions on evidence rather than intuition [20]. With the ability to make products information carriers, and the possibility for tracking and identifying products it will be possible use this information for decision support and controlling production [13]. Within the Industry 4.0 concept the collection and analysis of data is often referred to as Big Data [1]. APICS defines big data as "A collection of data and technology that accesses, integrates, and reports all available data by filtering, correlating, and reporting insights not attainable with past data technologies". Big data analytics is differentiated from traditional analytics in the way that the data processed is now available in higher volumes, with higher velocities and in more varieties than before [20]. Big data has the potential to improve demand forecasting, supply chain planning and other areas of production [21].

Augmented and virtual reality. Augmented reality systems can be used to assist in logistics, manufacturing, maintenance and training within an industrial context [22, 23]. The use of augmented reality combines information with the physical world to assist workers. Within logistics, pick-by-vision is a promising concept where AR technologies can enable fast, effective picking of parts and products. Work instructions for manufacturing and assembly operations can be given directly to workers through AR technologies [24]. These technologies show promise for assisting workers through integration of information into the working environment, reducing the cognitive load on workers and enabling better performance of various operations within logistics and manufacturing.

3.2. Identification and interconnectivity

The identification of objects and the interconnectivity available in the future factory essentially is what makes up the Internet of Things. Automated identification technology have been used industrially for a long time [25]. Now, however, by using network technology together with Auto ID technology, one is able to network information about products in a supply chain, and within a production facility [13], creating the Internet of Things, where all products, equipment and other objects within a facility can be connected. The possibility to uniquely identify products, equip them with sensors when delivered to the customer, and utilization of networking technology, can pave the way for new business models where servitization is more prominent. Although this is outside the scope of this paper, it is important to keep in mind the vast possibilities concerning identification and interconnectivity.

Sensors. The Smart Factory is equipped with sensors [4]. They are a vital part of a CPS, as they enable data acquisition from machines, equipment etc., and eventually creating self-aware and self-configuring manufacturing systems [12]. Sensor and actuator systems in the manufacturing equipment are enablers of acquiring real-time information on specific changes of the product, humans or processes in a facility [9].

Auto ID. ”Automated identification involves the automated extraction of the identity of an object” [25]. By enabling accurate and timely information about a specific item to be stored, retrieved and communicated, this information can be used to assist in automated decision-making and control functions relevant to that item. Identification technology has been developing very fast, seeing significant drops in the price of tags, equipment and infrastructure [26]. Radio frequency identification (RFID) is a type of Auto ID technology where radio frequency communications is used to identify and track objects attached with RFID tags [27]. It is considered as an enabler of the IoT within the Industry 4.0 concept [5].

Networking technology. Connecting different objects via a network allow them to interact and cooperate with each other [5, 28, 29]. Objects can include products, mobile phones, machines and other units. Having products and materials connected constantly to the network can give a complete overview of product flow, which gives the ability to work with lower safety stocks and react more quickly to changes in the market. Today’s networking technology also contributes to improve transport planning of finished goods with a supply chain by giving access to real-time status of all products in transport.

3.3. Seamless information flow

The factory of the future is digitalized with a high level of integration between the various subsystems, and it will be characterized by a seamless flow of information [6, 15]. A highly digitalized and vertically integrated factory will allow decision to be taken based on real-time information, improving the activities of production planning and control.

Real-time planning and control. Access to real-time information allows for continuous and real-time planning and control of manufacturing operations [13]. Moving towards real-time control requires new conceptual models for planning and control. Real-time control is today applied on machine and production line level. However, at planning levels, including scheduling within the MES systems, existing concepts are based on cyclic data processing and re-planning. Industry 4.0 technologies have the potential of enabling real-time planning and control of all planning activities.

Integration of IT systems. Vertical integration is one main feature of Industry 4.0 [1], thus a vertical integration from the shop floor, up through different sub-systems and to the ERP system will give a holistic and integrated management of information, which can improve manufacturing logistics. Integration of IT systems and digitalization of production in the context of manufacturing logistics will mean that the tasks required for PPC and directing the flow of materials through the factory is performed with the support of IT systems. This will first require that the required systems are implemented, henceforth that the systems are utilized. The complete integration for real-time production control will also require an Auto ID enabled shop floor, as presented by Arica and Powell [30]. The integration of IT systems is necessary to achieve fully the potential benefits of Auto ID technology [30]. Real-time control of production through a RFID enabled shop floor requires that the information from the identification of objects are transmitted to the higher level IT system, whether it is a MES system or an ERP system.

Cloud manufacturing. Cloud computing is essentially “on-demand” IT-services [31, 32]. An extension of this into manufacturing allows for the transition to service-based manufacturing, known as Cloud manufacturing (CMfg) [33]. The manufacturing resources and capabilities of companies can be linked to via cloud computing to potential customers of manufacturing services. The system can analyze the requirements and propose a service package, ranging from product design, manufacturing, testing and other manufacturing capabilities from the product life cycle. This connection between all manufacturing resources in a network, and the specific requirements of the customers, gives the ability to better utilize all the resources to give the desired output. Both the external and internal logistics can be optimized based on the requirements in manufacturing resources and capabilities.

3.4. Automation, robots and new production technology.

Further automation, utilization of robots as well as emerging production technologies, can have great implications for future production processes, giving the fourth category, *Automation, robots and new production technology.* Automation can be considered one of the main trends and expected developments within the Industry 4.0 concept [9]. One aspect of automation relates to manufacturing equipment, which will be characterized by the application of highly automated machine tools and robots [9].

Industrial robots. The cost of industrial robots are quickly decreasing, and the amount of robots utilized in industrial production will continue to increase [34]. Furthermore, as the cost is decreasing, their abilities are increasing, making them more autonomous, flexible and cooperative [35]. Industrial robots have traditionally required a precisely defined environment, with pre-planning and programming of their movements, but technological developments within Industry 4.0 are now changing this [34]. Industry 4.0 will also give developments in how humans are integrated in the production activities. Stock and Seliger [9] outline a development towards a production situation where robots and human workers are highly integrated and working collaboratively on joint tasks. Human-robot collaboration on the shop floor can be a measure for increasing technological support for operators in production environments where there are still significant proportions of manual operations.

3D printing. Additive manufacturing technology as 3D printing can be an enabler of more individualized production, which has been identified as one of the research streams within Industry 4.0 [7]. Additive manufacturing method's benefits over conventional manufacturing methods include batch reduction feasibility and design customization [36], which are relevant within the scope of Industry 4.0. Especially, supply chains where production of spare parts is a key part of the business due to high-level after-sales service are expected to benefit from effective use of additive manufacturing technologies [37].

Automatic Guided Vehicles. Automation and utilization of robots will also be of relevance in other areas apart from the production processes. Transportation, line feeding and material handling within a facility can also be exposed for more automated and robotized solutions. One example is Automated Guided Vehicles (AGV) systems for transporting material through a factory. Such systems are common in industry, although the aspect of autonomy makes such systems relevant in the Industry 4.0 context. Embracing technological developments such as autonomous and automatic systems for transportation and material handling can greatly benefit a company's internal logistics.

4. Implications of the Production Environment

The production environment can be described as the environment in which a production company operates. Thus, it concerns both external and internal factors. An important factor for describing a production environment is the customer order decoupling point (CODP). That is the point in the value creation process where a product is matched with an actual customer order. The placement of the CODP determines whether a company is make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO) or engineer-to-order (ETO). However, several other factors needs to be considered when describing a company's production environment. The topic of production environments have been widely described and studied [2, 38-41], and the production environment is often described in terms of specific variables or characteristic features. To structure the variables, they are by Olhager and Rudberg [39] grouped in three categories; product related, market related and manufacturing process related. Jonsson and Mattsson [2] and Schönsleben [40] do a similar grouping of the environmental variables.

The implications of the production environment for the fit of planning methods and the design and selection of production planning and control systems have been widely studied, and the applicability of PPC methods have been found to differ between production environments [2]. There is no one-size fits all approach to PPC, thus the characteristic features describing the production environment must be considered when designing the PPC system [2]. With the environmental variables' great impact on PPC, and thus companies' manufacturing logistics, this topic will be of high relevance also within the Industry 4.0 context.

A more general characteristic often used to describe production environments is the degree of repetitiveness of production [3]. According to Ptak and Schragenheim [42] a repetitive production company produces high volumes in low variety, and competes in the market based on price and/or lead time. Typical manufacturing strategies for such producers are make to stock, configure to order or assemble to order [42]. Repetitive production is repeated production of the same discrete products or families of products, which minimizes setups, inventory, and production lead time [43]. High volumes and low varieties mainly characterize repetitive produced products. Moreover, the Bills of Materials (BOMs) have typically few levels, and product routings are fixed and reliable [42]. In less repetitive environments, like the job shop environment, products are produced in several varieties, and product routings may vary [42]. This causes increased complexity in the flow of materials and for PPC and manufacturing logistics in general. Ptak and Schragenheim [42] further argue for the importance of different approaches to PPC for these two general types of production environments. Stevenson et al. [44] and Fernandes and Godinho Filho [45] conducted literature reviews to investigate the applicability of different PPC systems in environments of varying levels repetitiveness. The studies show that the applicability is highly dependent on the match with the production environment.

The multi-dimensional classification of production systems developed by MacCarthy and Fernandes [3] highlights how repetitiveness are dependent of characteristics, or variables, of the production system, or the production environment. By adding a variable describing the demand uncertainty or demand variation, all the categories (demand, product, and process) from Jonsson and Mattsson [2] are covered. Table 1 provides an overview of these variables, to be used when describing the production environment of the case companies.

Table 2 Sources for repetitiveness in production (Adapted from MacCarthy and Fernandes [3]).

Variables	Description	Scale
CODP	Placement of the customer order decoupling point	ETO, MTO, ATO, MTS
Automation level	Amount of automated processes	Low, Medium, High
Product structure complexity	Complexity of the average product structure	Low, Medium, High
Level of customization	The level of customization allowed at customer order entry	Customized products, Semi-customized products, Standard products
Number of product variants	The number of products offered to customers	Low, Medium, High
Layout	Organization of the facility shop floor	Fixed position layout, Functional layout, Group layout, Product layout
Material flow complexity	The complexity of the flow of material through the factory	High, Medium, Low
Demand variation	The variation and uncertainty in customer demand	High, Medium, Low

5. Methodology for case studies

To investigate how Industry 4.0 can improve manufacturing logistics, four case companies have been included in the study. The companies have been selected based on their stated goal of improving their internal flow of materials and general aim of improving their manufacturing logistics performance. Moreover, they represent a range of varieties of Norwegian manufacturing companies, where a key variable is the production environments the companies operate in. In a multiple case approach a replication logic is supposed to reveal support for contrasting results for predictable reasons [46], in this case the production environment. The data on the case companies were obtained through two main approaches:

- A mapping of each company’s production environment.
- A focus group survey.

The main information used for mapping the production environment stems from company visits with walk-arounds, workshops and meetings within the research project, which of the case companies are partners. The participants from the case companies in these meetings and workshops were mainly supply chain managers, production managers, and logistics managers. In addition, existing documentation of the case companies were made available for conducting the mapping. This information was then used to identify the characteristics of each case company.

To collect information from the case companies on their opinions and interpretations of Industry 4.0 and manufacturing logistics, a survey was made by following the general guidelines by Forza [47]. The survey contained questions concerning Industry 4.0 from a general perspective and from a manufacturing logistics perspective, covering the four categories discussed in section 3. It was presented to the case companies in a workshop at NTNU, May 10, 2016. The workshop participants were representatives from the four case companies, as well as researchers, professors and PhD. candidates affiliated with one or more of the case companies through their research. Having been a part of the research project, all participants had insights in the case companies, and were able to contribute in answering the survey together with the case companies' representatives. This way of conducting a survey is similar to what is termed "Focus Groups" by Kitzinger [48]. Focus groups capitalizes on communication between research participants in order to generate data, by taking a form of group interview [48]. Kitzinger [48] states that such a group process can aid in clarifying and exploring views that would be more difficult to access in a one to one interview. The focus group method is particularly relevant when the survey questions are open ended, and requires discussion to be answered [48]. This was the case for the majority of the questions in the survey. Despite this methodology's advantages, it is not as well suited for covering the depth of a particular issue. Although that was not the intention of this study, it must be noted that more in-depth and detailed studies on the topic should include different or additional research methodologies. The group interview format may cause the discussions to go off topic, which may leave survey questions not fully answered.

The answering of the survey was organized by dividing the workshop participants into four groups, one for each case company. The representatives for the case companies were assigned to their respective group, while the other participants were randomly distributed among the groups. Each group was instructed to answer the survey jointly, where one answer was mutually agreed upon for each question. This to reflect the group's interpretation and opinion as a whole. However, note that the data obtained from this survey results in only one qualitative answer from each company.

6. Case studies

This section will introduce the four case companies as well as the key findings from the mapping, analysis and survey results. For all the companies the analysis will refer to the categories presented in section 3 and which is listed in Table 1.

6.1. Kleven

Kleven Maritime AS includes the two shipyards Kleven shipyard and Myklebust shipyard, both located on the west coast of Norway. Shipbuilding at Kleven Maritime AS (from now Kleven) includes Platform supply vessels, Construction vessels, Seismic vessels, and Anchor-handling vessels.

Production at Kleven is characterized by ETO production. Ships are designed and engineered in close collaboration with the customer, allowing a very high degree of customization. This also makes Kleven's production one-of-a-kind production [49], producing one-offs every time. Production of ships requires a fixed position type of layout, where workers and materials are brought to the ship being produced. Compared to other types of layouts, the fixed position layout, which is common for shipbuilding and traditional ETO industries, is a factor for increasing the material flow complexity. This is also the case for Kleven.

Kleven focuses on modularization of products for achieving production efficiency. This means that ships are produced in modules, and then assembled into complete ships. The intention of this is to improve process control, production control and quality, and to reduce production lead times. Still, the typical throughput time is several months, up to 1-2 years. Naturally, the products produced by Kleven have a high product structure complexity, and a highly complex BOM with several levels, as well as a number of subassemblies. Consequently, only a small number of ships are produced each year.

Although Kleven are increasingly utilizing robots in the production, the manufacturing operations at Kleven are still mostly manual. The degree of automation and utilization of robots in the production is relatively low.

6.1.1. Towards Industry 4.0 for Kleven

The survey response from Kleven indicate that the company has no specific opinion whether Industry 4.0 is a realistic goal for the company or not, and the company is only to a small extent investigating the specific opportunities of it. It is seen as neither a threat nor a possibility for the company in the future. Although, if pursued, it is to some extent expected to improve the manufacturing logistics of the company. The most important focus areas for the company today are standardizing products and components and reducing throughput times. Improving the flow of materials and applying better methods and principles for planning and control is somewhat important, while reducing work-in-process and inventories are not of any specific importance.

Decision support. To some extent, data collection from the production processes is used to analyze, monitor and control production today. An increase of this data collection, utilizing intelligent sensors and Auto ID technology, is expected to have some improving impact on manufacturing logistics, although it is not an important part of the company's strategy for the future.

Identification and interconnectivity. Implementing Auto ID technology such as RFID is not expected to improve the internal flow efficiency at Kleven's shipyard significantly. However, it is stated that Auto ID can be a means to increase integration with suppliers in the future.

Seamless information flow. Today, Kleven has implemented an ERP system. The current IT infrastructure is to some extent expected to be suited for transition to Industry 4.0. More integrated IT solutions are expected to have a great positive impact on the manufacturing logistics of the company. However, Kleven does not have any specific focus on using more of the functionality of the installed ERP system. On the other hand, there are clear future ambitions on making the yard operations more digitalized.

Automation, robots and new production technology. Kleven state that this category is the most relevant category for Industry 4.0 applications in manufacturing logistics. It is expected that 3D printing will be possible to implement in future operations. Moreover, over the last years, effort has been put in to increasing the automation and utilizing robots in production. For example are some welding operations that previously were performed manually outside Norway now performed by robots at Kleven's shipyards in Norway. This is an enabler for maintaining production in Norway.

6.2. Brunvoll

Brunvoll AS develops and produces thruster systems for maneuvering and propulsion of several different types of advanced vessels. The company operates in a global market and is responsible for the whole thruster system. Business operations include design, production, sales and service. In addition to developing and producing new thruster systems, the after-sales market and service is an important part of the business for Brunvoll. This gives additional requirements in terms of e.g. spare parts production.

By producing thruster systems for advanced vessels, the business is highly dependent on the shipbuilding industry, which the main customers represent. Shipbuilding is a typical engineer-to-order industry [50], and this has implications on the production strategy and placement of the CODP for Brunvoll. Production is based on a combination of an ETO and MTO strategy, where customizations are allowed to a large extent. This gives a very high number of possible product variants. The shop floor layout is a combination of a fixed-position layout and cell layout, contributing to a high material flow complexity.

6.2.1. Towards Industry 4.0 for Brunvoll

Brunvoll consider Industry 4.0 to be a realistic goal. However, the company has not put significant effort into investigating possible opportunities of it. From an overall perspective, it is by the company viewed as a slight opportunity for increasing competitiveness, although its impact on manufacturing logistics is only considered minor. The most important focus areas related to manufacturing logistics for Brunvoll are improving the flow of materials, reducing throughput time and inventories of raw materials and finished goods. Improving the methods and principles for planning and controlling production is part of this focus. Increasing the use of IT and integrating IT solutions are also issues to some extent, while standardization of products and components is considered less important.

Decision support. Data capture and analysis is only to a small extent used to monitor and control production at Brunvoll today. The logistics data that are collected includes processing time, work-in-process, delivery time and delivery reliability. The company to some extent agree that improved data collection and analysis will improve the manufacturing logistics, and it is part of the production strategy for the coming years.

Identification and interconnectivity. Implementing Auto ID is not expected to be applicable for improving the internal material flow efficiency in the factory significantly. However, the company state that product identification, and especially product tracking, can be a measure to increase integration with customers. Brunvoll expect that this will enable better integration of the value chain.

Seamless information flow. Brunvoll has currently implemented an ERP system and a PLM system. In addition, implementing a MES system is under consideration. The company also expects that increased utilization and integration of IT systems will have major positive implications on manufacturing logistics, allowing more seamless flow of information. The company also states that there is a potential to utilize more of the functionality available in IT systems currently in place.

Automation, robots and new production technology. The use of additive manufacturing like 3D printing is highly relevant for Brunvoll as it is expected to be applicable to a large extent. Implementing such technology is also expected to contribute to reduced complexity related to manufacturing logistics to a large extent. Furthermore, the percentage of automated processes is expected to increase over the coming years, although not significantly.

6.3. Ekornes

Ekornes is a furniture production company, headquartered in Ikornnes on the west coast of Norway. They are positioned within the medium/high-end of furniture products, with the aim to be a leading actor and producer of branded goods within the home furniture industry, both in the national and international market. The company's most known product is the Stressless reclining chair, but sofas, coffee tables etc. are also part of the product portfolio.

Ekornes has a strong focus on allowing customization of products. However, the customization is typically in terms of skin type and color of chairs. On the other hand, it gives a large number of possible product variants. To be able to deliver their products to customers efficiently, the company has employed a combination of MTO and ATO production strategy. The effect in reality is that finalization of products are done after customer orders have been received. When a customer order is received, with the specific customization in terms of skin type and color, the skin is cut and sewed before the chair is assembled.

Production is organized in a functional shop floor layout, with different departments responsible for each of the main production stages. One of the characteristics of the functional layout type is a complex material flow, although if seen on a higher level all products follow the same overall route through the different departments for each of the main production stages as e.g. the sewing department.

6.3.1. Towards Industry 4.0 for Ekornes

Ekornes' survey response indicate that Industry 4.0 is a realistic goal and an opportunity for the company, but they have today only to a certain extent investigated the possibilities and opportunities of it. It is stated that Industry 4.0 on a general basis will improve the manufacturing logistics in the company to a large extent. Improving the efficiency of the material flow is a major focus area of Ekornes. Mainly this is to be achieved by reduced throughput times and increasing IT utilization.

Decision support. Today, Ekornes collects and capture large amounts of logistics data. These include throughput time, processing time, work-in-process, and delivery reliability. However, such data are not used for analysis in a large extent. On the other hand, the company believes that using such data for analysis will improve the manufacturing logistics of the company significantly.

Identification and interconnectivity. The applicability of Auto ID technology like RFID in the production at Ekornes is considered high. However, the company states that implementation of Auto ID for product track and trace is believed to give only a moderate improvement in the flow efficiency of goods and material.

Seamless information flow. Ekornes has today an ERP and MES system installed. Although projects have been initiated to investigate the possibilities for implementing both APS and PLM systems. More integrated IT-systems can improve the manufacturing logistics to a large extent. In addition, there are functionalities of the current IT systems that are not utilized. However, the company has no specific focus related to increasing the IT system utilization.

Automation and New production technology. Production technologies such as 3D printing is not expected to have any impact on the manufacturing logistics of Ekornes. On the other hand, the company expects that the level of automation and utilization of industrial robots will increase in the coming years.

6.4. Pipelife

Pipelife Norge AS is a part of the international Pipelife group. The group is headquartered in Austria, and is one of Europe's leading producers of plastic pipes. Pipelife Norge AS (from now Pipelife) is the Norwegian division of the group and produces plastic pipes for use in various areas, including water supply and sewage, heating ventilation and sanitation, cable protection, wiring and gas pipes.

Pipelife has a MTS production strategy, with highly standardized and repetitive production of pipes in large quantities. The CODP is placed at the finished goods inventory, from where products are picked and shipped. Thus, no customization is allowed. Product variety and complexity is low, with only 1-2 levels in the BOM. Pipelife aims for cost advantage through economies of scale in their mass production of plastic pipes, and production is organized in a highly automated product line shop floor layout, with changeover times and set-up times being major factors for planning and control. In this layout, the material flow is very streamlined, with a low material flow complexity.

6.4.1. Towards Industry 4.0 for Pipelife

Pipelife's response on the survey indicates that the company sees Industry 4.0 as a very realistic goal. The company is also largely investigating possible applications. Furthermore, Industry 4.0 in general is considered a great opportunity for the company, and is expected to improve manufacturing logistics significantly. To achieve more efficient internal logistics, improving the flow of materials and increasing IT-utilization are the primary focus areas of Pipelife, together with reducing changeover times. Finding better methods and principles for planning and control and reducing inventories of raw materials and finished goods are also of a certain importance. Standardization of components, increasing flexibility and reducing work-in-process are less important focus areas.

Decision support. Production data is captured and analyzed at Pipelife today, and the company state that this will be increasingly important for improving manufacturing logistics in the future. Over the last three years, the quality of information available has improved significantly, but information is only to some extent accurate, timely and available for use. The sharing efficiency is also moderate. However, the company now has a strong focus on applying real-time capture and analysis of information for decision support and improving manufacturing logistics performance.

Identification and interconnectivity. Implementation of Auto ID is expected to be highly applicable for Pipelife, and it is expected to give significant improvements to manufacturing logistics performance. Auto ID technology such as RFID is expected to be applicable for improving production planning and control activities, purchasing and inventory control.

Seamless information flow. Pipelife has today implemented an ERP system and a MES system, and the current IT infrastructure is expected to be well suited for transition to Industry 4.0. Pipelife also states that more integrated IT solutions will have a positive impact on the manufacturing logistics of the company. On the other hand, Pipelife has to a large extent a focus on increasing the current IT utilization to apply more of the available functionality.

Automation and New production technology. Production technologies such as 3D printing are not considered relevant for Pipelife. On the other hand, a large amount of the production processes is already automated. This, as well as the level of autonomy, is expected to increase over the next years.

7. Discussion of case study findings

The mapping of the case companies' characteristics revealed the difference in production environments for the four companies. Table 3 provides a comparison of the characteristics of each of them. In addition to the variables previously described in Table 2, this table includes the "Relative degree of repetitiveness". This is derived from the preceding variables and their total contribution to the repetitiveness. Each of the companies have then been given a degree of repetitiveness, relative to the other companies. Kleven has the least repetitive production, while Pipelife has the most repetitive production.

Table 3 Classification of case companies based on repetitiveness in production.

Variables	**Kleven**	**Brunvoll**	**Ekornes**	**Pipelife**
CODP	ETO	MTO	ATO	MTS
Automation level	Low	Low	Medium	High
Product structure complexity	High	High	Medium	Low
Level of customization	Customized	Customized	Semi-customized	Standard
Number of products	High	High	Medium	Low
Layout	Fixed position layout	Fixed position and cell layout	Functional layout	Product line layout
Material flow complexity	High	High	Medium	Low
Demand variation	High	High	Medium	Low
Relative degree of repetitiveness (from 1-4)	1	2	3	4

Further, the applicability of the Industry 4.0 technologies described in section 3 has been evaluated based on the focus group survey response. This is shown in Table 4 below.

Table 4 Applicability of Industry 4.0 technologies in case companies.

	Applicability in case companies			
Industry 4.0 technologies	**Kleven**	**Brunvoll**	**Ekornes**	**Pipelife**
Artificial intelligence	Low	Low	Medium	High
Big data analytics	Medium	Medium	High	High
Augmented and virtual reality	High	High	Medium	Medium
Sensors	Medium	Medium	High	High
Auto ID	Low	Medium	Medium	High
Networking technology	Low	Medium	High	High
Real-time control	Medium	Medium	High	High
Integration of IT systems	Medium	Medium	High	High
Cloud computing	Medium	Medium	Medium	Medium
Industrial robots	Medium	Medium	High	High
3D printing	High	High	Low	Low
Automatic Guided Vehicles	Low	Low	High	High

Note: Applicability has been evaluated in terms of two factors; the ease of implementation, and the potential positive impact on manufacturing logistics performance.

As indicated by Slack et al. [13] and MacCarthy and Fernandes [3] the shop floor layout is an important source of creating complexity in a production environment, as it has an impact on the material flow complexity. Especially, in a fixed-position layout and a functional layout the material flows are not unidirectional. Shipbuilding is characterized by a fixed position layout, where materials, workers and production equipment have to be brought to the product being processed. In such a setting, monitoring and data collection of what is happening can be difficult and implementing real-time control to any extent can be more problematic than with layouts where the material flow is less complex, such as in the product line layout. On the other hand, one can argue that the need for identifying, tracking and tracing products is more valuable when the material flow is complex.

High product varieties can give implications for implementing Auto ID. It is expected that uniquely identifying a high number of product variants produced in low volumes is more difficult than uniquely identifying a low number of variants produced in high volumes. Auto ID is considered as a key enabler for real-time monitoring and control, which consequently can be difficult to implement for a company where product variety is high.

Although the sample analyzed only contains four companies, the results from the mapping and survey indicate that there is a relation between the repetitiveness of production, CODP placement and the companies' perceived Industry 4.0 applicability. Fig. 1 shows the relationship between repetitiveness in production of the four case companies and the companies' perceived potential of applying Industry 4.0 technologies in manufacturing logistics. Of the four case companies included, Pipelife, characterized by a product line layout and MTS strategy, as well as low complexity in product structure and material flow, has the highest level of production repetitiveness. Pipelife is also the company that sees the highest potential for approaching and benefitting from Industry 4.0 and are most active in pursuing it. They see very high potential benefits from implementing Industry 4.0 technologies related to identification of products and interconnectivity to improve manufacturing logistics. In comparison, Ekornes and Brunvoll have lower levels of production repetitiveness, and ATO/MTO and MTO/ETO strategies, respectively. These two companies state the potential benefits of Industry 4.0 to be medium/high, and are not exploring the specific possibilities of Industry 4.0 in the same way as Pipelife. Lastly, Kleven is the most ETO-oriented company of the four, with the lowest level of production repetitiveness. Moreover, Kleven see less potential benefits from Industry 4.0 than the other companies in this study, and has the longest way to go to reach an Industry 4.0 level of production.

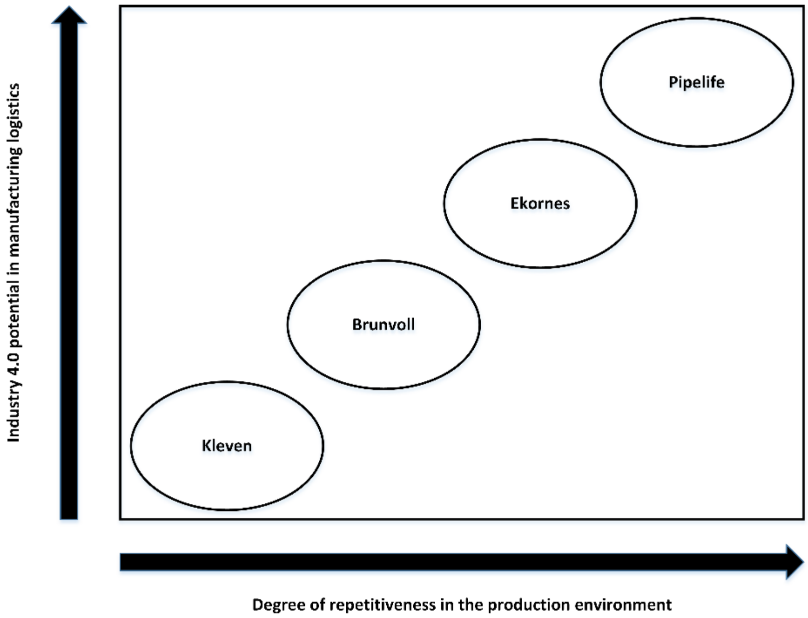

Fig. 1 Relationship between repetitiveness in production and perceived potential of applying Industry 4.0 technologies

While the degree of repetitiveness is a critical factor for the choice of PPC system [3], and the choice of planning methods is dependent on the production environment [2], this study further indicates that the degree of repetitiveness in the production environments also affects the applicability of Industry 4.0. Characteristics of the production environment that causes increased complexity of the manufacturing logistics processes is expected to reduce, or at least imply on, the applicability Industry 4.0 technologies. Thus, the differences in production environments call for different approaches to Industry 4.0, and conducting analyses of the production environment is a prerequisite before Industry 4.0 can be applied to manufacturing logistics. The mapping of the case companies' production environment, the survey results and the evaluation of the applicability of Industry 4.0 technologies have been used to develop a proposition suggesting that: There is a relationship between the applicability of Industry 4.0 technologies and the degree of repetitiveness in the production environment, and the applicability is higher in more repetitive production environments.

There are several aspects of the repetitive production environment that positively affects Industry 4.0 applicability. The low complexity of material flows, layout, and product structures in the repetitive production environment eases production control and monitoring. Thus, collecting data may is more convenient, giving both higher volumes and quality of production data. Industry 4.0 applications for data collection and analysis are thus easier to implement. In the process industry and the fast moving consumer goods industry, which are examples of industries with highly repetitive production, the level of instrumentation and the use of sensors for monitoring production is high. These industries typically have rigid production systems, with a high level of automation. As Industry 4.0 goes beyond the automation of production processes, the repetitive production environment is closer to the Industry 4.0 vision than environments characterized by a high amount of manual processes. All these aspects facilitates the transition to Industry 4.0 as it is described in [1].

Nevertheless, although the applicability of Industry 4.0 may be higher in repetitive production environments, the potential positive impact of Industry 4.0 applications may be equal, and possibly even higher, for the most non-repetitive production environments. The application of Industry 4.0 in non-repetitive production environments, typical for ETO and one-of-a-kind production, will thus be a highly relevant research topic for the coming years.

8. Conclusions, limitations and further research

This paper has discussed and presented a proposition regarding the fit of Industry 4.0 applications for manufacturing logistics in different production environments. The sample of case companies investigated in this study indicate that companies with low degree of production repetitiveness, high material flow complexity and high degree of ETO production are least suited for a transition to Industry 4.0 in terms of manufacturing logistics. In addition, these companies seem to be less enthusiastic of Industry 4.0. Companies with a higher degree of production repetitiveness, lower material flow complexity and lower degree of ETO production seem, in comparison, to be less challenged by the production environment. Moreover, they are more actively investigating the possibilities Industry 4.0 technologies can offer.

A general roadmap or set of guidelines for moving towards Industry 4.0 has not been identified in this study. Moreover, the findings from the case studies and analysis of the survey suggest that a roadmap for Industry 4.0 will be dependent on the characteristics of the production environment of each specific company. Especially the characteristics of the production environment that affect the repetitiveness of production will have implications on the applicability of Industry 4.0 in the context of manufacturing logistics. Hence, there is no "one-size fits all" approach when it comes to Industry 4.0. A company specific or industry specific approach seems necessary to reap the potential opportunities and benefits from Industry 4.0.

Conducting a study on more than one case company limits the level of detail of the mapping and analysis of the case companies. This is a limitation to the study. Moreover, with a scope aiming at manufacturing logistics, several of the other aspects related to Industry 4.0 have been neglected.

Further research should include more detailed investigations of how Industry 4.0 technologies can be applied in manufacturing logistics and where in the logistics system each technology application is most relevant. Moreover, a similar, larger scale survey should be conducted to investigate further the relationship between production environments and Industry 4.0 potential and application of the technologies. Research is also needed to investigate how manufacturing companies characterized by a non-repetitive production can apply Industry 4.0 technologies. Especially, there is a need to investigate if one-of-a-kind manufacturing also can benefit from Industry 4.0 applications, as this study show that it may be challenging due to such companies' low degree of repetitiveness. More specifically addressing the characteristics of the production environment that affects the repetitiveness of production, and how each of them affects applicability of industry 4.0 applications, may also be a topic for future research.

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REFERENCES

1. Kagermann, H., Helbig, J., Hellinger, A., and Wahlster, W. (2013). *Recommendations for Implementing the strategic initiative INDUSTRIE 4.0: securing the future of German manufacturing industry; final report of the Industrie 4.0 working group*. Forschungsunion.
2. Jonsson, P. and Mattsson, S.-A. (2003). *The implications of fit between planning environments and manufacturing planning and control methods.* International Journal of Operations & Production Management, 23(8): p. 872-900.
3. MacCarthy, B.L. and Fernandes, F.C.F. (2000). *A multi-dimensional classification of production systems for the design and selection of production planning and control systems.* Production Planning & Control, 11(5): p. 481-496.
4. Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., and Hoffmann, M. (2014). *Industry 4.0.* Business & Information Systems Engineering, 6(4).
5. Hermann, M., Pentek, T., and Otto, B. (2016). *Design principles for industrie 4.0 scenarios*, in *49th Hawaii International Conference on System Sciences (HICSS)* IEEE. p. 3928-3937.
6. Wang, S., Wan, J., Li, D., and Zhang, C. (2016). *Implementing smart factory of industrie 4.0: an outlook.* International Journal of Distributed Sensor Networks.
7. Brettel, M., Friederichsen, N., Keller, M., and Rosenberg, M. (2014). *How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective.* International Journal of Mechanical, Industrial Science and Engineering, 8(1): p. 37-44.
8. European Commission (2004). *Manufuture: A Vision for 2020, Assuring the Future of Manufacturing in Europe.*
9. Stock, T. and Seliger, G. (2016). *Opportunities of sustainable manufacturing in Industry 4.0.* Procedia CIRP, 40: p. 536-541.
10. Lin, H.W., Nagalingam, S.V., Kuik, S.S., and Murata, T. (2012). *Design of a global decision support system for a manufacturing sme: towards participating in collaborative manufacturing.* International Journal of Production Economics, 136(1): p. 1-12.
11. Lee, E.A. (2008). *Cyber physical systems: Design challenges*, in *11th IEEE International Symposium on Object Oriented Real-Time Distributed Computing (ISORC), 2008*. IEEE. p. 363-369.
12. Lee, J., Bagheri, B., and Kao, H.-A. (2015). *A cyber-physical systems architecture for industry 4.0-based manufacturing systems.* Manufacturing Letters, 3: p. 18-23.
13. Slack, N., Chambers, S., and Johnston, R. (2010). *Operations management*. Pearson Education.

14. Anderl, R. (2014). *Industrie 4.0-advanced engineering of smart products and smart production*, in *19th International Seminar on High Technology, Technological Innovations in the Product Development, Piracicaba, Brazil*.
15. Lucke, D., Constantinescu, C., and Westkämper, E. (2008). *Smart factory-a step towards the next generation of manufacturing*, in *Manufacturing systems and technologies for the new frontier. The 41st CIRP Conference on Manufacturing Systems*. Springer: Tokyo, Japan. p. 115-118.
16. Radziwon, A., Bilberg, A., Bogers, M., and Madsen, E.S. (2014). *The smart factory: exploring adaptive and flexible manufacturing solutions.* Procedia Engineering, 69: p. 1184-1190.
17. Yoon, J.-S., Shin, S.-J., and Suh, S.-H. (2012). *A conceptual framework for the ubiquitous factory.* International Journal of Production Research, 50(8): p. 2174-2189.
18. Dopico, M., Gomez, A., De la Fuente, D., García, N., Rosillo, R., and Puche, J. (2016). *A vision of industry 4.0 from an artificial intelligence point of view*, in *International Conference on Artificial Intelligence (ICAI)*. The Steering Committee of The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp). p. 407-413.
19. Li, B.-h., Hou, B.-c., Yu, W.-t., Lu, X.-b., and Yang, C.-w. (2017). *Applications of artificial intelligence in intelligent manufacturing: a review.* Frontiers of Information Technology & Electronic Engineering, 18(1): p. 86-96.
20. McAfee, A., Brynjolfsson, E., Davenport, T.H., Patil, D., and Barton, D. (2012). *Big data.* The management revolution. Harvard Bus Rev, 90(10): p. 61-67.
21. Sagiroglu, S. and Sinanc, D. (2013). *Big data: A review*, in *International Conference on Collaboration Technologies and Systems (CTS)*. IEEE. p. 42-47.
22. Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. (2015). *Industry 4.0: The future of productivity and growth in manufacturing industries.* Boston Consulting Group: p. 14.
23. Reif, R. and Walch, D. (2008). *Augmented & Virtual Reality applications in the field of logistics.* The Visual Computer, 24(11): p. 987-994.
24. Wang, X., Ong, S., and Nee, C. (2016). *A comprehensive survey of augmented reality assembly research.* Advances in Manufacturing, 4(1): p. 1.
25. McFarlane, D., Sarma, S., Chirn, J.L., Wong, C., and Ashton, K. (2003). *Auto ID systems and intelligent manufacturing control.* Engineering Applications of Artificial Intelligence, 16(4): p. 365-376.
26. Ilie-Zudor, E., Kemény, Z., Van Blommestein, F., Monostori, L., and Van Der Meulen, A. (2011). *A survey of applications and requirements of unique identification systems and RFID techniques.* Computers in Industry, 62(3): p. 227-252.
27. Xiao, Y., Yu, S., Wu, K., Ni, Q., Janecek, C., and Nordstad, J. (2007). *Radio frequency identification: technologies, applications, and research issues.* Wireless Communications and Mobile Computing, 7(4): p. 457-472.
28. Atzori, L., Iera, A., and Morabito, G. (2010). *The internet of things: A survey.* Computer networks, 54(15): p. 2787-2805.
29. Shrouf, F., Ordieres, J., and Miragliotta, G. (2014). *Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm*, in *International Conference on Industrial Engineering and Engineering Management (IEEM) IEEE* IEEE. p. 697-701.
30. Arica, E. and Powell, D.J. (2014). *A framework for ICT-enabled real-time production planning and control.* Advances in Manufacturing, 2(2): p. 158-164.
31. Xu, X. (2012). *From cloud computing to cloud manufacturing.* Robotics and computer-integrated manufacturing, 28(1): p. 75-86.
32. Zhang, L., Luo, Y., Tao, F., Li, B.H., Ren, L., Zhang, X., Guo, H., Cheng, Y., Hu, A., and Liu, Y. (2014). *Cloud manufacturing: a new manufacturing paradigm.* Enterprise Information Systems, 8(2): p. 167-187.
33. Li, B.-H., Zhang, L., Wang, S.-L., Tao, F., Cao, J., Jiang, X., Song, X., and Chai, X. (2010). *Cloud manufacturing: a new service-oriented networked manufacturing model.* Computer integrated manufacturing systems, 16(1): p. 1-7.
34. OECD (2017). *The Next Production Revolution: Implications for Governments and Business*. OECD Publishing Paris.
35. Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. (2015). *Industry 4.0: The future of productivity and growth in manufacturing industries.* Boston Consulting Group, 9.
36. Holmström, J., Partanen, J., Tuomi, J., and Walter, M. (2010). *Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment.* Journal of Manufacturing Technology Management, 21(6): p. 687-697.
37. Khajavi, S.H., Partanen, J., and Holmström, J. (2014). *Additive manufacturing in the spare parts supply chain.* Computers in industry, 65(1): p. 50-63.

38. Lödding, H. (2012). *Handbook of manufacturing control: Fundamentals, description, configuration*. Springer Science & Business Media.
39. Olhager, J. and Rudberg, M. (2002). *Linking manufacturing strategy decisions on process choice with manufacturing planning and control systems.* International Journal of production research, 40(10): p. 2335-2351.
40. Schönsleben, P. (2007). *Integral logistics management: Operations and supply chain management in comprehensive value-added networks*. CRC Press.
41. Newman, W.R. and Sridharan, V. (1995). *Linking manufacturing planning and control to the manufacturing environment.* Integrated Manufacturing Systems, 6(4): p. 36-42.
42. Ptak, C.A. and Schragenheim, E. (2003). *ERP: tools, techniques, and applications for integrating the supply chain*. CRC Press.
43. APICS *Online Dictionary*.
44. Stevenson, M., Hendry, L.C., and Kingsman, B.G. (2005). *A review of production planning and control: the applicability of key concepts to the make-to-order industry.* International journal of production research, 43(5): p. 869-898.
45. Fernandes, F.C.F. and Godinho Filho, M. (2011). *Production control systems: Literature review, classification, and insights regarding practical application.* African Journal of Business Management, 5(14): p. 5573-5582.
46. Yin, R.K. (2013). *Case study research: Design and methods*. Sage publications.
47. Forza, C. (2002). *Survey research in operations management: a process-based perspective.* International journal of operations & production management, 22(2): p. 152-194.
48. Kitzinger, J. (1995). *Qualitative research. Introducing focus groups.* BMJ: British medical journal, 311(7000): p. 299.
49. Wortmann, J.C. (1992). *Production management systems for one-of-a-kind products.* Computers in Industry, 19(1): p. 79-88.
50. Gosling, J. and Naim, M.M. (2009). *Engineer-to-order supply chain management: A literature review and research agenda.* International Journal of Production Economics, 122(2): p. 741-754.