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「The Evolution of Production Systems from Industry 2.0 through Industry 4.0」

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This paper discusses production systems with a focus on the relationships between product supply and customer demand in the context of Industry 2.0 - 4.0. One driver of production evolution is changes in customer demand over time, which is categorized into several dimensions. Major production systems – flow line, Toyota production system (TPS), job shop, cell, flexible manufacturing system, and *seru* – have been developed and applied to supplies to match different demand dimensions over time. For each production system, two questions are addressed: *what* and *how*. Comparisons between *seru* with TPS and cell are given. The possibilities of a future smart factory equipped with internet of things (IoT) are discussed. The demand dimensions of Industry 4.0, the product architecture change in the automobile industry, and the impact of 3D printing are elaborated. Potential applications of lean and *seru* principles for Industry 4.0 are presented.

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Abstract

This paper discusses production systems with a focus on the relationships between product supply and customer demand in the context of Industry 2.0 - 4.0. One driver of production evolution is changes in customer demand over time, which is categorized into several dimensions. Major production systems – flow line, Toyota production system (TPS), job shop, cell, flexible manufacturing system, and *seru* – have been developed and applied to supplies to match different demand dimensions over time. For each production system, two questions are addressed: *what* and *how*. Comparisons between *seru* with TPS and cell are given. The possibilities of a future smart factory equipped with internet of things (IoT) are discussed. The demand dimensions of Industry 4.0, the product architecture change in the automobile industry, and the impact of 3D printing are elaborated. Potential applications of lean and *seru* principles for Industry 4.0 are presented.

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1. Introduction

The 20th and 21st centuries are ages of industry (Crainer, 2000) in which manufacturing is important. Industries have and are still undergoing three industrial revolutions (sometimes called Industry 1.0, 2.0, and 3.0). A continuous concern for manufacturing firms is the mismatch between supply and demand within value chains. This paper reviews and focuses on the relationship between product supply and customer demand in the context of Industry 2.0 - 4.0.

Many factors affect supply-demand relationships, such as volume, variety, time, quality, price, brand, and design. For each Industry X.0, this paper only considers primary demand dimensions that are important for customers. Customer demand is represented by various dimensions and supply is realized by appropriate production systems.

Industry 1.0 (from the 18th to 19th centuries) brought human activities from focusing on agriculture to the industrial society. The demand for industrial products in Industry 1.0 had only one dimension – product volume. We can call this demand environment as the *Simple Market*. In

Industry 1.0, supplies were smaller than demands. Outputs of industrial products could not satisfy the demands from society. A central idea in Industry 1.0 came from the economics of Adam Smith's *Wealth of Nations*, in which price was described as an automatic tool to adjust mismatch between supply and demand. If supplies were smaller than demands, prices rise. If supplies were larger than demands, prices fall. Product variety was very low and most commodities were agricultural products, so price adjustment was a good tool for balancing the supply-demand mismatch at that time. Adam Smith is considered the "Father of Economics" and *Wealth of Nations* was the first publication on modern economics.

Industry 2.0 (from the end of the 19th century to the 1980s) was the period when industrial products burgeoned both in volume and variety. Major technological innovations included electricity, electronic and mechanical devices, and cars. Products of Industry 2.0 are still widely used today. A milestone of Industry 2.0 was Frederick Taylor's *The Principle of Scientific Management,* which was the first publication on modern management theory. Taylor is considered the "Father of Management". The demand during Industry 2.0 had two dimensions – volume and variety. We can call this demand environment as *Stable Market*. Two innovators, Henry Ford and Taiichi Ohno, practiced and extended Taylor's theory. Ford addressed the shortage of supply in product volumes by using mass production assembly lines. Ohno addressed various customer interests in product varieties by developing the Toyota production system (TPS), the precursor to lean.

Industry 3.0 (from the 1980s to today) is characterized by technological innovations such as change from analog to digital, which had big impact, especially on the electronics industry. The product architecture of most electronics products changed from integral to modular, accompanied by a dramatic reduction in average product life cycles. The demand for products during Industry 3.0 increased to three dimensions – volume, variety, and delivery time. We can call this demand environment as *Volatile Market*, which caused flow line and TPS malfunctions. Flexible manufacturing systems (FMSs) and *serus* are used by industries as supply approaches to match the three dimensions of demand.

Industry 4.0 is an initiative with technology innovations such as internet of things (IoT), big data, electric vehicles (EV), 3D printing, cloud computing, artificial intelligence, and cyber-physical systems. Industry 4.0 has attracted attention from governments, industries, and researchers. Many aspects of Industry 4.0 are unknown and uncertain, such as the demand dimensions of customers and the future product architecture of electric vehicles. The next section provides a literature review on the evolution of production systems.

2. Literature Review

Production systems have evolved through several paradigms. A number of studies have discussed the evolutionary path of production systems from different perspectives. Mourtzis and Doukas (2014) classified manufacturing chronologically as craft production, American production, mass production, lean production, mass customization, and global manufacturing. They suggest that each production system is operated based on pull and/or push modes. For example, American production, mass production, and lean production push. Craft production and global manufacturing pull. Mass customization uses both push and pull.

Hopp and Spearman (2001) reviewed manufacturing history through management evolution. They begin in 4000 B.C., when Egyptians coordinated large-scale projects to build pyramids, through James Watt inventing the steam engine. Adam Smith published *Wealth of Nations* around 1770. Fredrick Taylor published *The Principles of Scientific Management* and Henry Ford introduced the first moving automotive assembly line in Highland Park, Michigan in the 1910s. Taichi Ohno published *Toyota Seisan Hoshiki* on the Toyota production system in 1978. Hopp and Spearman emphasized the scientific mechanisms underlying each production system. For example, they investigated the influences of system variabilities (from customers, in-process, and suppliers) to the manufacturing processes by applying mathematical tools.

Many studies focus on the evolution of lean production. Fujimoto (1999) summarized the evolutionary path of TPS by investigating Toyota's organizational capabilities in manufacturing. He proposed a three-layer model to interpret how TPS gradually and cumulatively evolved through the three layers of routinized manufacturing capability, routinized learning capability, and evolutionary learning capability. Holweg (2007) investigated the evolution of the research at the MIT International Motor Vehicle Program that led to the conception of the term lean production. He presented a timeline of key events within Toyota, the dissemination of lean production outside Toyota, and major publications and concepts of lean production. Hines et al. (2004) reviewed the evolution of lean production theories. They applied McGill and Slocum's (1993) four type classification of organizational learning to classify the evolution of lean production theories into the four stages of cells and assembly lines, shop-floor, value stream, and value systems.

This paper focuses on the evolution of production systems in the context of supply-demand relationships. A short value chain with three players – component supply, final product assembly, and market demand – is analyzed. Historical changes in demand dimensions from Industry 2.0 to 3.0 are given. Industrial production systems are discussed and compared. For final product assembly, assembly line, TPS, and *seru* are analyzed. For component supply, job shop, cell, and FMS are discussed and compared. We highlight the differences between *seru* and conventional manufacturing cells that are based on group technology. The *what* and *how* of each production system is addressed. For example, what is *seru* production? How should a *seru* production system be constructed and managed? To the best of our knowledge, this is the first paper that uses supply-demand relationships to analyze the drivers for production system evolution over time. We summarize the demand drivers of Industry 2.0 and 3.0, and predict the demand drivers in the future Industry 4.0. The possibilities of a future smart factory equipped with IoT are discussed.

3. Flow Line, TPS, Job Shop, and Cell for Industry 2.0

The struggle for the *Simple Market* (with the one dimension of product volume) of Industry 1.0 was the shortage of supplies, which were generated with craft production implemented by workshops of families and/or small communities. This shortage of supply difficulty was addressed by using mass production in Industry 2.0.

The *Stable Market* of Industry 2.0 had the two dimensions of product volume and product variety. In the beginning of Industry 2.0, the pressure was how to increase product volume with low cost. By using mass production, Ford matched high volumes with its Model T assembly line innovation. An assembly line for mass production is a system that can supply large product volumes with low cost (the question of *what*). The main enablers (the question of *how*) of an assembly line include dedication of the assembly line (i.e., no product variety, one line for each product model), standardization of components and operations, specialization of workers and equipment (i.e., one worker and equipment for each operation), short operation times, and the attempt to balance workloads. In the early 1920s, Ford had 2/3 of American automobile market share. The price of a Model T was reduced from $850 in 1908 to $250 in 1924. From the 1920s, customer desires were becoming diverse. A single model (the black Model T) no longer satisfied all customers. Alfred Sloan (1964) of General Motors addressed this problem by using a divisional organization structure (one division for each model). In contrast, the organizational structure of Ford was flat. In 1940, Ford's market share fell to 18.9% and GM rose to 47.5%. The performance of GM was good, but the real champion that could satisfy both volume and variety simultaneously became Toyota.

Krafcik (1988) coined the term lean for the TPS created by Ohno (1988). TPS is an integrated system that can supply products to meet both requirements of product volumes and product varieties. Lean is a production concept that is investigated by researchers and imitated by many companies. Many research and practical papers, reports, and books were published in various media to describe TPS and lean. The underlying management principles and theoretical mechanisms of lean TPS are well-known. Excellent analysis and review papers on lean are de Treville and Antonakis (2006), Hines et al. (2004), and Narasimhan et al. (2006). The evolution from mass to lean TPS productions illustrates the trade-off between efficiency and flexibility (Adler et al., 1999; de Treville et al., 2007). The *what* and *how* problems related to TPS are next described.

A TPS is an integrated production system that generates products to satisfy requirements of volumes and varieties simultaneously with minimum resource waste. This definition coincides with Krafcik (1988), who defined lean as "Requires the use of the less of anything through the production of the product including less of labor, space, tools investments and time, which can lead to keeping the less inventory and achieving few inventory defects, resulting in variety and a greater amount of production". Two critical cores of Krafcik's definition are "the less of anything" and "resulting in variety and greater amount of production", which are the essence of our definition.

A large number of TPS enablers have been reported. Some of the core enablers include just-in-time material system (JIT-MS), seven wastes, *heijunka*, multi-skilled workers, quick setup and changeover, and *keiretsu*. The TPS copes with product variety with a mixed-product-model assembly line, which can accommodate different models simultaneously. Quick changeover and setup are required to achieve high flexibility and *heijunka* is applied for high efficiency. Workers are partially cross-trained, which means that each worker can perform more than one operation. JIT-MS (i.e., the right components, in the correct place, at the right time, in the exact amount) is applied to control material flows. A scientific analysis of the lean-enabling technique is the factory physics of Hopp and Spearman (2001). They emphasized a balance among capacity utilization, work in process, and variability. For example, if variability in a system increases, either work in process must increase or capacity utilization must decrease. de Treville and Antonakis (2006) employed this understanding of factory physics to emphasize that lean is realized by maximizing capacity utilization and minimizing buffer inventories, thus reducing system variability (related to supplier, customer, or in-process). Shah and Ward (2007) made a similar point that a TPS is achieved by eliminating wastes by concurrently minimizing or reducing variability.

Mass and TPS assembly lines assemble final products. The parts and components of products are usually produced using job shops and/or cells and/or FMSs, in which the part variety is usually higher than the final assembled product variety. A job shop tends to manufacture small lots of a variety of parts. Most parts in a job shop require a long setup time between each operation and a process sequence of machines. A job shop is created by locating similar machines together, resulting in a functional layout. For example, drilling machines are usually contained in one area and grinding machines in another area. In a job shop, flexibility is high and efficiency is low.

Cellular manufacturing (CM) is an application of group technology. One objective of CM is to efficiently cope with the production of a high variety of parts. Cells are converted from job shops with functional layouts to improve efficiency (Yin and Yasuda, 2006). A cell consists of a machine group and a part family. The first step in CM system design is the identification of part families and machine groups to form manufacturing cells so as to process each part family within a machine group with minimum intercell movements of parts. This identification is referred to as the cell formation problem. Parts in the same family have similar machining sequences. Machines in a cell are arranged to follow this sequence. In this way, parts flow from machine to machine in their processing sequence, resulting in an efficient machining flow that is similar to an assembly line. For each part family, the volume of any particular part may not be high enough to utilize a dedicated cell. The total volume of all parts in a part family should be high enough to utilize a machine cell well. CM attempts to flexibly accommodate high variety and simultaneously efficiently take advantage of flow lines (Celikbilek and Suer, 2015) .

4. FMS and *Seru* for Industry 3.0

The *Volatile Market* of Industry 3.0 has the three demand dimensions of product volume, product variety, and delivery time. Delivery time is the time-period from when a customer places an order until the customer receives the product.

Product life cycles of electronics products decreased during the Industry 3.0 period. In Japan, the average life cycle for electronics products is about six months (Yokoi, 2014). This motivates manufacturing firms to consider responsiveness as a primary objective. TPSs cannot adequately achieve responsiveness. The average life cycle of automobiles was around four to six years (Sato, 2015). Toyota's production planning and control period is around two months (Aoki, 2012). Customer waiting times can be relatively long. For example, in 2016, Toyota's delivery time for a Prius averaged six to eight months (Nikkei-Business, 2016). Lean's failure in responsiveness has been partially answered by management scholars. For example, Wessel et al. (2016) noted that "all companies' internal systems – their metrics, resource allocation processes, incentives, approaches to recruitment and promotion, and investment strategies – are set up to support their existing business model. These systems are generally well established and extremely difficult to change, and they often conflict with the needs of digital business models." This is similar for lean, which was designed to reduce demand variability in the two dimensions of volume and variety. It is extremely difficult to change a current system, for example, a mixed product assembly line, to fit the desire to reduce demand variability in three dimensions.

FMSs started production in the mid 1970s to early 1980s. An FMS is an integrated, computer-controlled complex of automated material handing and computer numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of part types. A fully automated FMS can attain the efficiency of well-balanced, machine-paced transfer lines, while utilizing the flexibility that job shops have to simultaneously machine multiple part types (Stecke and Solberg, 1981; Stecke, 1983; Browne et al., 1984).

A *seru* production system is an assembly system that has been adopted by many Japanese electronics companies. The first English paper on *seru* production is Yin et al. (2008), which describes and analyzes the success of *seru* production systems in Canon and other Japanese companies. The underlying management and control principles of *seru* are given in detail in Stecke et al. (2012), Yin et al. (2008, 2017), and Liu et al. (2014). Roth et al. (2016) review the last 25 years of OM research and provide eight promising research directions. One research direction mentioned that "*seru* production systems are more flexible than Toyota's production system, and they represent the next generation of lean production that has recently been introduced to operations" (pp. 1476).

Seru was explicitly created as an alternative to the TPS because TPS had malfunctioned in an innovative industry where the primary objective is responsiveness (see Stecke et al., 2012 and Yin et al., 2008, 2017 for details). *Seru* began in 1992 when Sony replaced a video camera assembly line with several compact *serus*. Soon after, Canon dismantled its assembly lines to adopt *seru* systems. Sony and Canon are considered pioneers in implementing the *seru* production system. Huge benefits have been reported from *seru* production. For example, *seru* can reduce lead time, setup time, WIP inventories, finished-product inventories, cost, required workforce, and shop floor space. *Seru* also influences profits, product quality, and workforce motivation in a positive way.

An important performance of the *seru* production system is that it can quickly respond to manufacture product varieties with fluctuated volumes, matching supply with Industry 3.0's demand. By applying *seru*, delivery time is reduced. Variety and volume are easily handled. For example, Sony Mexico's variety and efficiency increased 650% and 30%, respectively. Similarly, Canon's variety and efficiency increased 200% and 300%, respectively (Stecke et al., 2012; Yin et al., 2017).

The following discusses the two questions (*what* and *how*) related to *seru* production systems. A *seru* is usually an assembly system that consists of some (usually simple) equipment and one or more workers that produce one (sometimes more) products. A *seru* production system consists of one or more *serus*. *Serus* within a *seru* system are quickly reconfigurable, i.e., they can be constructed, modified, dismantled, and reconstructed frequently in a short time.

There are three types of *serus*, called divisional *serus*, rotating *serus*, and *yatais*. They represent the evolutionary development of *serus*. A divisional *seru* is a short, often U-shaped, assembly line staffed with several partially cross-trained workers. Tasks within a divisional *seru* are divided into different sections. Each section is in the charge of one or more workers. A rotating *seru* is often arranged in a U-shaped short line with several workers. Each worker performs all required tasks from-start-to-finish without interruption. Tasks are performed on fixed stations, so workers walk from station to station. A worker follows the worker ahead of her or him, and is also followed by the worker behind her or him. A *seru* with only one worker is called a *yatai*.

The TPS-based assembly line became inefficient because of an inability to change very frequently to match small-volume demands. The typical *seru* creation process in Sony and Canon can be summarized as follows (Yin et al., 2017). Assembly lines were dismantled and replaced with divisional *seru* systems through resource co-location and removal/replacement, cross training, and autonomy. The technique of *karakuri* (involves procedures to discover and appropriate the useful functions of expensive equipment into inexpensive self-made equipment) is applied to replace expensive dedicated equipment by inexpensive self-made and/or general-purpose equipment that can be duplicated and redeployed as needed by *serus*. As cross-training progresses, divisional *serus* evolve into rotating *serus* and *yatais.*

The management and control of a *seru* production system can be described as follows. A management principle called just-in-time organization system (JIT-OS) is developed to match supply with demand. JIT-OS (i.e., the correct *serus*, in the right place, at the appropriate time, in the exact amount) is an extension, or upgrade, of Toyota's traditional JIT-MS (i.e., the correct components, in the right place, at the appropriate time, in the exact amount). Their mechanisms are similar. The main difference is the focus from components to organizations (i.e., *serus*). The typical implementation of JIT-OS is as follows. Configure the *seru* production system so that the correct *serus* are in the right place, at the appropriate time for the set of products to be assembled. This involves either the relocation or relayout of current *serus* or the creation of new *serus* for both new products or model changes. Then determine the appropriate number of *serus* and/or number of workers within *serus* to handle the various required product volumes. Yin et al. (2008) and Stecke et al. (2012) illustrate practical cases of JIT-OS implementations in Canon and Sony. Yin et al. (2017) show that most JIT-OS problems are NP-hard. Efficient approaches to solve these problems need to be developed. In summary, JIT-OS is a key mechanism to help *serus* achieve responsiveness. Reconfigurability of *serus* is a prerequisite to implement JIT-OS.

5. Comparisons of *Seru* with the TPS and Cells

Differences between *seru* and TPS and cell are now discussed. The differences are emphasized from the four aspects of strategy, operations, technique, and performance. There are two types of cells, GT-based cells that machine parts and assembly cells. Johnson (2005), Sengupta and Jacobs

(2004), and Gong et al. (2011) discuss assembly cells.

Differences from the *strategic perspective* are as follows.

1. Objective: A primary objective of both TPS and a GT cell is to deal with product variety (e.g., TPS's mixed product line and a cell's part family). A secondary objective of the TPS and a cell is to cope with product volume. A primary objective of *seru* is to pursue responsiveness. A secondary objective is to cope with product variety and volume.
2. Position within a value chain: A GT-based cell is usually designed to machine parts. *Serus*, TPS lines, and assembly cells are assembly systems, usually in the final stage of production. A supply chain can be constructed by using GT cells or FMSs in the upstream and *serus,* TPS, or assembly cells or lines in the downstream.
3. Conversion process: A GT cell is converted from a job shop (from a functional layout). A *seru* is converted from a traditional assembly line.

Differences from the *operations perspective* are as follows.

4. JIT-OS: JIT-OS manages and controls a *seru* system. JIT-OS cannot be applied to TPSs or cells since they are not quickly reconfigurable.
5. Virtual organization: When business environmental uncertainty becomes high, cells encourage the use of virtual cells. *Serus* can cope with environmental uncertainties by combining JIT-OS and reconfigurable *serus*.
6. Autonomy: *Serus* emphasize responsible autonomy that enables worker teams in *serus* to schedule production, but workers are not allowed to carry out procedures however or whenever they choose (Yin et al., 2017). In contrast, cells emphasize choice autonomy that enables workers to have some freedom concerning procedures and timing (Hyer and Brown, 1999).

Differences from the *technique perspective* are as follows.

7. Group technology: Cellular manufacturing is an application of group technology. A GT cell machines a part family that contains a few similar part types. In contrast, *serus* can be dedicated to a single product or to several products for a short production time, and then be

dismantled and reconfigured.

8. Heijunka: The TPS and an assembly line need *heijunka* to balance the workloads among different products. *Serus* do not need *heijunka* since most *serus* are dedicated for a short period of time before reconfiguration.

9. Equipment: Compared to TPS and cell equipment, the equipment of *serus* is simple.

10. *Karakuri*: *Karakuri* is a prerequisite for creating *seru* systems. *Karakuri* is not used in the TPS and GT cells.

11. Cross-training: *Seru* systems encourage completely cross-trained workers (e.g., *yatai*). Workers in the TPS and GT cells are partially cross-trained.

Differences from the *performance perspective* are as follows.

12. Reconfigurability: *Serus* are reconfigurable and not fixed. TPS and assembly lines are fixed and not reconfigurable.

13. Concurrent operations: For a specific product, a *seru* system can be concurrent or parallel. A product can be assembled simultaneously by several *serus*. In contrast, TPS and assembly cells are not duplicated. Products are assembled with other products together in a mixed TPS line. Products are assigned to a part family and machined in a single GT cell. Therefore, a *seru* system is more reliable than a TPS or cellular manufacturing system because of redundancy.

Key points of the differences between *seru* and TPS and cells are summarized in Table 1.

Table 1. *Seru* versus TPS and cells

		Seru	TPS	GT-based Parts Cell	Assembly Cell
Strategy	Objective	responsiveness	variety	variety	variety
	Supply Chain Position:	assembly	assembly	parts supplier	assembly
	Conversion Process	assembly line	--	job shop	assembly line
Operations	JIT-OS	yes	no	no	no
	Virtual Organization	no	no	yes	yes
	Autonomy	responsible	no	choice	choice

Technique	Group Technology	no	no	yes	yes
	Heijunka	no	yes	yes	yes
	Equipment:	simple	general/specialized	general	general
	Karakuri	yes	no	no	no
	Cross-training	completely	partially	partially	partially
Performance	Reconfigurability	yes	no	no	no
	Concurrent Operations	yes	no	no	no

6. Potential Manufacturing for Industry 4.0

Industry 4.0 was an initiative established by the German government in 2012 (Kagermann et al., 2013) to maintain its strong competitiveness in manufacturing industries. Similar promotions are advocated in other industrial countries. For example, the United States proposed a smart manufacturing plan (Smart Manufacturing Leadership Coalition, 2011) and suggested connecting everything with the Internet using IoT (Porter and Heppelmann, 2014, 2015). The Japanese government published "Society 5.0" – a smart system that covers smart community, smart infrastructure, smart factory, and others. China created a plan of "Chinese Manufacturing 2025" to foster Chinese manufacturing shifting to high value-added and becoming a global leader.

Most keywords in the above initiatives of different countries are technology related. These include sensors, IoT, big data, cloud computing, artificial intelligence, automation, robots, cyber-physical systems, 3D printing, and electric vehicles. Some potential effects of these technologies for future manufacturing have been discussed (Kersten et al., 2017a, 2017b; Ivanov et al., 2016; Theorin et al., 2017; Liao et al., 2017; Thoben et al., 2017) in the three layers of data and data collection and communication devices, physical structures of smart factories, and advanced data analysis to support factory operations.

Many analysts and policymakers think that the rise of big data analytics and mobile technology should spur the development of smart cities. Lim and Mack (2017) see a less optimistic urban future, because digitization and crowdsourcing may undermine the foundations of a megacity economy. They consider 3D printing as a disruptive new technology, because it has transformed the economies of scale into economies of one or few. Many Asian manufacturing centers can expect to see widespread disruption to their economies and work forces. Robots, artificial intelligence, and the human cloud can make the notion of offices obsolete. Industries must adapt to technological change and start to plan for a disrupted future.

Schröder et al. (2014) analyzed supply chain risk management in the context of Industry 4.0. With some technologies of Industry 4.0 such as cloud computing and cyber-physical systems, a supply chain can become more flexible and transparent. On the other hand, supply chain management may be faced with new challenges. Increased data volume and availability in real-time require new infrastructures and approaches to handle information. The connection of humans, objects, and systems may allow dynamic, real-time improved, self-organizing, and cross-company value creation networks. More autonomy may be given to production systems. Decision-making competences may be transferred from a hierarchical organized system to a decentralized, semi-autonomous collective of machines, equipment, operators, and mobile devices. Relevant management and control systems should be developed to adapt to modifications in hardware, software, and communication technology of Industry 4.0.

The changes and requirements in production management principles, in particular, changes in customer demands in the era of Industry 4.0, are not clear. This section attempts to begin to fill this gap. First, Industry 4.0 literature that discusses customer requirements is reviewed. Then, a real case, Xiaomi, is used to demonstrate possible future customer demands. Finally, the evolution of customer demands and how this evolution could reshape production principles are discussed.

6.1. Smart Manufacturing for Industry 4.0

An important competitive advantage for a company is its capability to realize individual requirements of diverse customers. Companies pursue this competitiveness by applying mass customization (MC), which attracts attention from researchers and practitioners since the late 1980s (Da Silveira et al., 2001; Fogliatto et al., 2012). MC is a strategy that creates value by some form of company–customer interaction at the product design, fabrication, and assembly stages to create customized products (Kaplan et al., 2006). MC should provide enough product variety and customization that nearly every customer can find exactly what they want (Pine, 1993).

It can be difficult to effectively implement MC (Gilmore and Pine, 1997; Salvador et al., 2009; Fogliatto et al., 2012). Manufacturers should apply appropriate management and control principles to organize manufacturing systems to realize individual customer requirements. A manufacturing system should be efficient, flexible, responsive, and able to find an appropriate management and control principle, hopefully quickly (Zawadzki and Zywicki, 2016). Traditional manufacturing systems may find it difficult to achieve these requirements. For example, the TPS is flexible and efficient. Effective approaches have been developed to suggest better management and control principles (Hopp and Spearman, 2001). But its responsiveness is slow. *Seru* can respond to customer requirements with high efficiency and flexibility. Useful *seru* management and control principles (i.e., JIT-OS) need further development. Currently, most JIT-OS applications are based on factory managers' experiences.

Because of the importance of MC and the difficulty to realize MC with current manufacturing systems, some research suggests that smart manufacturing under the environment of Industry 4.0 may be a key to help implement MC strategy. Zawadzki and Zywicki (2016) suggested smart product design and production control for efficient operations in a smart factory to realize an MC strategy. A desire for customized products in combination with decreasing product life cycles begs for organizational structure changes from TPS to self-improving smart manufacturing systems that can utilize data to quickly react (e.g., reconfigure) to personalized customer orders (Brettel et al., 2014). These management and control problems are usually NP-hard (Yin et al., 2017). Some studies have suggested efficient mathematical models that use big data to manage and control manufacturing processes in smart factories (Ivanov et al., 2016, 2017).

6.2. Xiaomi Case

Smart products in the era of Industry 4.0, like smartphones, can be connected for data exchange among users, makers, and possibly related third parties. Similar to the smartphone, connected products may consist of the three core modules (Porter and Heppelmann, 2015) of a physical module (such as mechanical and electrical components), a smart module (such as sensors, software, and microprocessors), and a connectivity module (such as protocols, antennae, and networks to product clouds). Most products of Industry 3.0 do not involve the third connectivity module. The successful business case of Xiaomi is now provided to deduce some possible demand dimension changes from Industry 3.0.

Xiaomi is a Chinese smartphone maker who released its first smartphone in August 2011, and became the world's 3rd largest smartphone maker in October 2014, following Samsung and Apple. The rapid success of Xiaomi relied on its unique business model, which can be depicted as a triangle (Askci-Corporation, 2014). The three angles of the triangle are hardware, software, and the internet, which are similar to our above description of a smart products' physical module, smart module, and connectivity module, respectively. Xiaomi's uniqueness is in its Xiaomi-internet that consists of a Xiaomi cloud, Xiaomi chat, Xiaomi WIFI, and Xiaomi library. The Xiaomi-internet is an online network (and can be regarded as an IoT application) that allows customers to communicate with the Xiaomi staff, hardware and software suppliers, and other customers. Customers' specific requests are encouraged to be submitted to the Xiaomi-internet. These requests are responded to quickly and then may be realized in hardware and/or software designs, manufacturing, and internet service. Xiaomi customers' loyalties and enthusiasm are high.

6.3. Demand Dimensions for Industry 4.0

Based on the literature review and Xiaomi's case, we can deduce some future demand dimensions of Industry 4.0 as follows.

- ✧ Variety: Companies may introduce multiple models for each product. There may be one or more standard products consisting of standard modules. These standard modules consist of hardware and/or software that provide standard functions for general customers. Some customer participation in product design can be important. There could be other standard platforms where customers can suggest or request specific personal designed modules and/or components to realize possible individual customization. A platform is an unfinished product that consists of underlying core components or modules to form a common structure from which derivative products can be efficiently developed and produced. We call the latter case *customer participated individual customization* (CPIC).

- ✧ Time: In Industry 4.0, product life cycles may become more uncertain. The life cycle of a platform may be short or long. In contrast, life cycles of individual modules that are personally designed to provide specific functions may be short because of possible frequent upgrades. Requested delivery time may be short.
- ✧ Volume: In Industry 4.0, volumes of standard products and platforms may be high or middle. In contrast, volumes of personal designed modules may be very low. Volumes of standard modules may fluctuate drastically with a wide range from low to high.

A future smart manufacturing system should be organized in conformance with the above Industry 4.0's customer demand dimensions. A possible configuration is given in Figure 1. The construction of IoT and big data cloud allows communications among customers, assemblers, suppliers, and other service providers. A smart manufacturing system may consist of two parts. The first part is an *information* system (cloud computing and design of products and processes in

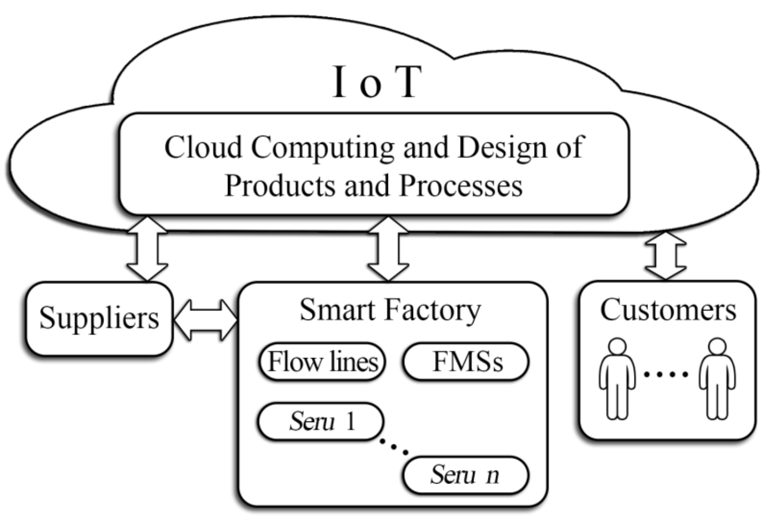

Figure 1. An example of a smart manufacturing system for Industry 4.0

Figure 1 that can act as a brain of the smart manufacturing system. The information system implements two tasks. Customized modules and/or components are articulated during product design to realize CPIC based on received specific customers' requests. A supply decision is made to meet (or not) customer desired product varieties, volumes, and times. The decision consists of a coordination policy for the supply chain and a management and control principle (e.g., JIT-OS) for the smart factory. Advanced optimization and technologies such as artificial intelligence and deep learning may be used to assist in finding an appropriate supply decision.

The second part of a smart manufacturing system is a *physical* system that consists of a smart factory and its suppliers. The smart factory assembles or fabricates final products, platforms, and/or modules. A smart factory can contain various production systems. A possible JIT-OS may be generated by the information system and may be used to allocate customer orders to different production systems to achieve demands with smooth production flows. Possible production systems such as flow lines, FMSs, and *serus* can be differentiated in their applications as in the following possible scenarios. For high production volumes and low varieties (e.g., standard products, platforms, and modules), flow lines equipped with high speed machines, tools, and robots may be used to pursue scale efficiency. For medium production volumes and moderate varieties (e.g., standard and/or customized products, platforms, and modules), FMSs or flow lines may be used to pursue efficiency and flexibility with mixed product models. For high and/or low production volumes and high varieties (e.g., customized products and modules, and possible module upgrades) that require responsiveness (e.g., short lift cycle and/or delivery time), *seru* production systems or FMSs may be applied.

7. Modular Design for Vehicles

During Toyota's annual general meeting in June 2017, president Akio Toyoda introduced some new challenges and opportunities, such as electric vehicles, automated vehicles, connected cars, and car sharing business models. Information technology companies such as Google and Apple may become strong competitors in some of these applications (Nihon Keizai Shimbun, 2017). To address these challenges and opportunities of electric vehicles, automated vehicles, connected cars, and car sharing business models, Toyota plans to intensify the following areas. Toyota plans to invest in artificial intelligence and an in-house company system (that is, a business unit financially, independent of the corporation) to quickly and flexibly take charge of business projects related to these challenges and opportunities.

Deployment of the Toyota new global architecture (TNGA) is another one of the above-mentioned areas. TNGA is a product design method that was developed by Toyota in 2015. Toyota plans that half of its products in 2020 should be developed by using TNGA (Nikkan Kogyo Shimbo, 2017). Similar design methods have been utilized by other automotive companies, such as Renault and Nissan's common module family, Volkswagen's modulare querbaukasten (translated from German to modular transversal toolkit), and Volvo's scalable product architecture. The key concepts of all of these automotive design methods are the utilization of common components and the adoption of modular architectures.

The trend of architecture change from integral to modular in the automotive industry has been discussed in the literature. Fixson (2005) and Ro et al. (2007) discussed the impact of modularity on automotive supply chains. They note that modularity can reduce new model development costs and can act as a viable MC strategy for the automotive industry. Pandremenos et al. (2009) reviewed modularity concepts for the automotive industry. They predicted that the product architecture of next generation vehicles will change from integral (with high production volume and low flexibility) to modular (with middle to high production volume and flexibility). Cabigiosu et al. (2013) conducted an experimental design to explore the component-vehicle interface definitions adopted by assemblers and suppliers. They showed that the interface design is determined by the degree of vertical integration, knowledge scope, and strategic focus of an assembler, as well as the supply chain coordination mechanisms between the assembler and its suppliers. Lampon et al. (2017) analyzed the European automotive manufacturers' production networks and showed that the use of modular architecture can improve coordination by increasing manufacturing flexibility.

Product architecture can be defined as the way in which the functional elements of a product are allocated to physical components and the way in which these components interact (Ulrich and Eppinger, 2008). Ulrich (1995) defined product architecture as follows: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components.

Product architectures are either modular or integral. Previous studies have shown that the choice between these two architectures for a product is important and can be a key driver to a manufacturing firm's performance (Fine et al., 2005; Ramachandran and Krishnan, 2008). Examples of modular architecture include electronics products such as desktop computers and consumer electronics. In a modular architecture, the mapping from functional elements to physical components is one-to-one. The interfaces among interacting physical components are loosely coupled. Most components of a modular product are interchangeable and the interfaces are standardized. Advantages of modular architecture include an increase in product variety, components commonality, easy upgradability, and low cost.

Examples of integral architecture include luxury motorcycles, game software, and automobiles. In integral architecture, the mapping from functional elements to physical components is not one-to-one. The interfaces among interacting physical components are often tightly coupled. For an integral product, a change in some functional element or component can lead a change to other components in order for the overall product to work correctly. Modular architecture can realize local product performance that can be achieved by using one or several components. For example, the speed of a computer is mainly determined by its CPU. In contrast, global product performance depends on many components and can only be improved through an integral architecture. For example, the mass and/or size of a product are determined by almost every component within a product. Function sharing and geometric nesting are design strategies that are frequently employed to minimize mass and/or size (Ulrich, 1995; Yin et al., 2014). Advantages of integral architecture include increased product performance, and the creation of unsubstitutable competitive competences.

A possible trend in the automotive industry may be that gasoline vehicles may be gradually replaced by EVs. Gasoline engines and gasoline may be replaced by motors and batteries. Similar to most electronics products, there is high possibility that the architecture of EVs could be modular (Nihon Keizai Shimbun, 2010; Kawahara, 2010; Uyama, 2013). Compared to a gasoline-engine vehicle, the number of EV components may be reduced dramatically. For example, the number of gasoline engine components is around 10,000 - 30,000. The number of electric motor components may be around 80 - 100. More important, many components such as motors and batteries may become standardized components in the automotive industry (Nihon Keizai Shimbun, 2010). Then, similar to the computer industry, core components (e.g., CPU) may be procured easily from suppliers and assembly operations of EVs maybe become simple.

Recall that in Industry 3.0, the electronics industry underwent an architectural change from integral to modular. These motivated Japanese electronics makers to replace TPS production's mixed assembly lines with assembly *serus* to increase responsiveness. A similar change in production methods may occur in EVs. The variety of EVs may increase. Product life cycles may shorten. Responsiveness could become a priority for the automotive industry. Production systems using *seru* principles could become appropriate in the future.

8. 3D Printing

Garrett (2014) suggests that the impact of 3D printing may be disruptive and revolutionary, and that the impact could last for several decades in the areas of manufacturing, value chains, environments, global economies, and geopolitics. 3D printing for real products is still expensive and is mostly used to generate prototypes and mockups. Applications are expanding. According to a survey of more than 100 companies, two-thirds were using 3D printing (Curran, 2016). Among these two-thirds applications, 13.1% were producing products and/or components and 53.5% were experimentations and prototype productions. Gebler et al. (2014) estimated that 3D printing in manufacturing is expected to mature within the next 10 years and to change the input and output of the processes used to produce low volume, customized, and possibly some high-value products. An article (Tumbleston et al., 2015) in *Science* introduced possible technologies for 3D printing that may speed the adoption of 3D printing in various industrial applications.

Some advantages of 3D printing for industry have been presented (Economist, 2011). For example, 3D printing can print many geometric structures. It may simplify the product design process. It is relatively environmentally friendly.

Some 3D studies for possible future applications are as follows. Dong et al. (2016) used a multinomial logit model to analyze the optimal assortment from a potential set of product variants to compare a manufacturing firm's strategy under two possible types of flexible production technologies, traditional flexible technology and 3D printing. They found that 3D printing may allow a firm to choose a larger set of variants than the optimal assortment using traditional flexible technology without significant profit loss. Westerweel et al. (2016) considered the impact of 3D printing on component design. They evaluated the lifecycle costs of components to find that component reliability is crucial to the success of 3D printing.

Song and Zhang (2016) examined the use of 3D printing on a logistics system for spare parts inventory design. They specified which parts should be printed when needed and which parts should be stocked. When a demand for a part encounters a stockout, sometimes it can either be backlogged or manufactured by using a 3D printer. They demonstrated that adopting 3D printing may yield some cost savings and this impact may increase in part variety. A similar spare parts inventory logistics design problem was discussed in a case study (Ivan and Yin, 2017), which investigated a Russian car dealer that sells Japanese cars. Spare parts for the automobiles have to be procured from Japan. By installing a 3D printer at the dealer in Russia to generate some simple plastic parts, the dealer sometimes can reduce supply lead time.

The degree of individual customization may increase because a 3D printer can generate many geometric structures. Such 3D printing may take longer and be more expensive than conventional machining. 3D printed parts may not be as sturdy and might not meet tolerances. Supply lead time may be reduced by installing 3D printing locally. Product life cycles may shorten. Responsiveness could increase.

9. Conclusions

Various types of production systems, such as flow line, TPS, job shop, cell, FMS, and *seru*, have been used with success. This paper reviews the evolution of production systems from the viewpoint of supply-demand mismatch or balance. Figure 2 summarizes the evolution of Industry 1.0 – 4.0 over time.

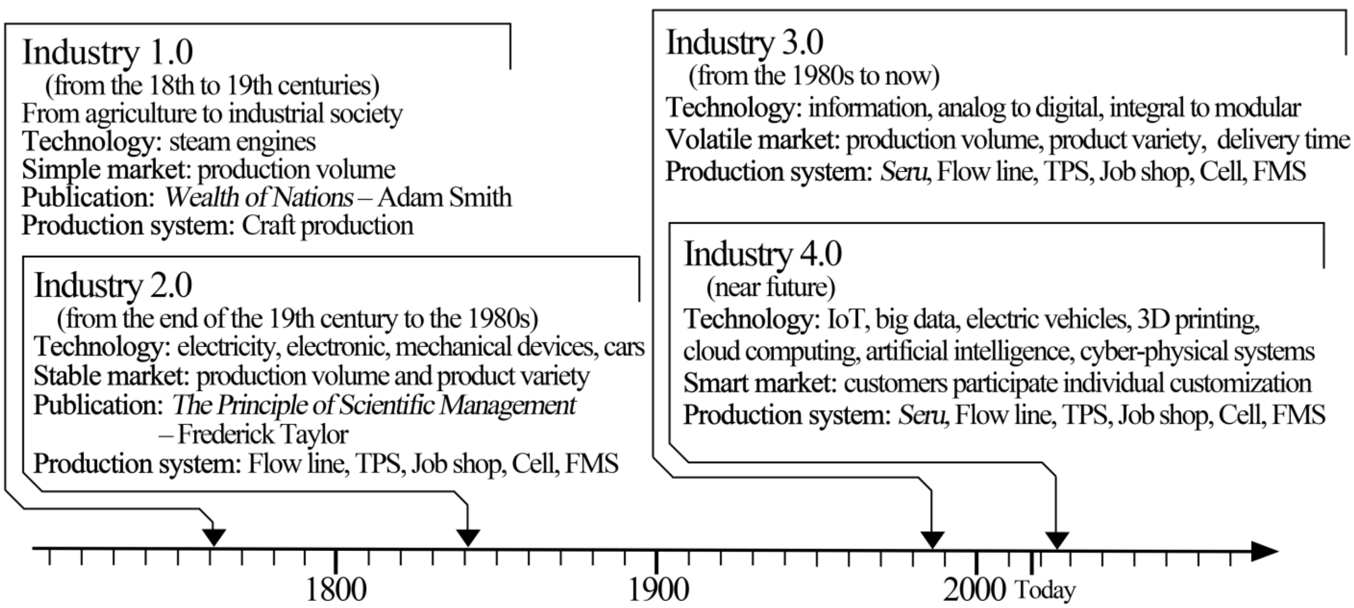

Figure 2. Time line of Industry 1.0 – 4.0

Customer demand is partitioned into different dimensions to describe the market characteristics of Industry X.0. Appropriate production systems have been utilized to match different demand dimensions over time. Comparisons of *seru* with the TPS and cells are provided. Potential manufacturing for Industry 4.0, possible modular design for EVs, and the outlook of 3D printing applications are suggested.

From early craftsmanship workshops to today's modern factories, the practices and operations of manufacturing systems have evolved over these 200 years. A study of the evolution of production systems can provide hints for the possibilities of future production systems. Industry

4.0, EVs, and 3D printing are in their early stages. Many aspects of these areas are unknown and uncertain. Because of the interdisciplinary characteristics of the three areas of business, engineering, and information technology, studies have been performed from different perspectives. Future studies that incorporate and integrate these three areas are recommended.

Three future research directions are as follows. First, big data collection and evaluation should become easier because of IoT. From Figure 1, the information system of a smart manufacturing system may have to generate a management and control system (e.g., JIT-OS) to allocate customer orders for processing on different production systems. Most JIT-OS decision problems are NP-hard (Yin et al., 2017). Efficient approaches that may utilize advanced optimization or artificial intelligence or deep learning need to be developed. Second, the customer demand dimensions of Industry 4.0 are uncertain and unknown. Industry 4.0 combines many technologies such as sensors, automation, robots, and cyber-physical systems. These technologies may require changing the operational procedures of a production system. How a production system adapts to an environment with new technologies and customer demand dimensions has to be investigated. Third, detailed case studies that are rigorous, deep, and insightful to explain how to create, manage, operate, and maintain production systems in the context of Industry 4.0 is suggested.

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