UiT THE ARCTIC UNIVERSITY OF NORWAY

Faculty of Engineering Science and Technology

Development of Small-scale Intelligent Manufacturing System (SIMS)

— A case study at Stella Polaris AS

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Master's thesis in Industrial Engineering … June 2017

Foreword

At the present global scenario connected through Internet, the world is creating and sharing ideas all the time. New thinking can be shared immediately. Within the manufacturing industry, we are now witnessing the emergence of the new paradigm called "Industry 4.0", which was first proposed as "Industrie 4.0" in Germany in early 2014 [1] and indicated the beginning of the 4th Industrial Revolution. This new trend is currently shared and followed as a common goal among academics and industries throughout the world and stimulates a lot of new thinking. Along with Industry 4.0, many similar initiatives have been put forward and under research and development (R&D), such as Factory of the Future (FoF) in the UK [2], Smart Factory in Italy and Spain [3], Smart Industry in Sweden [4], Smart Manufacturing in the US, and the Internet of Things (IoT), etc. In Norway, there are mainly two initiatives relating to Industry 4.0: Logistic 4.0 at the Norwegian University of Science and Technology (NTNU), and Small-scale Intelligent Manufacturing System (SIMS) at the Arctic University of Norway (UiT) in Campus Narvik.

This Master's thesis project is a part of the Master program in Industrial Engineering in the Department of Industrial Engineering under the Faculty of Engineering Science and Technology at UiT, Campus Narvik. The project is under the research topic of SIMS, aiming at developing the initiative of small-scale intelligent manufacturing systems. Through this work, a better understanding of basic questions such as why doing SIMS, what is SIMS or how SIMS should be like, how to achieve SIMS, and so on, should be achieved.

Preface

Manufacturers in the resourceful Northern Peripheral and Arctic (NPA) region are mostly small and medium-sized enterprises (SMEs). Facing challenges primarily caused by the size and location of enterprises, these SMEs are constantly driven to take new measures to survive from the fierce competition against its domestic and international competitors, under the industrial environments of globalization of markets, rapidly changing customer needs, manufacturing paradigm shift to personalization, and the coming era of Industry 4.0.

Originally aiming at enhancing the competitiveness of SMEs in the NPA region, a novel concept for small-scale intelligent manufacturing systems (SIMS) has been put forward and introduced [5] regarding its design objectives and applicable technologies. The major purpose of this project is to further develop the concept of SIMS in order to support SMEs in overcoming challenges from changing customer needs and unstable market conditions, transforming their manufacturing processes towards personalized production, and adapting themselves to the upcoming Industry 4.0 era.

In this project work, an extensive literature review on manufacturing systems was conducted (see in Chapter 2 and Chapter 3), covering diverse aspects from definition, components, levels, types of process, progresses in manufacturing methods including both technological and managerial approaches, etc. The literature study has helped to better understand the background, purpose, and benefits of developing SIMS, which are described in Chapter 4. In Chapter 5, a novel architecture for defining a manufacturing system from the supply chain perspective is built. In Chapter 6, a hierarchical framework of SIMS features and technological approaches towards objectives is developed. Managerial approaches towards some of the objectives are also listed. Key issues to be solved in developing SIMS are discussed in Chapter 7. Besides the theoretical frameworks developed for SIMS, a case study is discussed in Chapter 8, regarding the possible implementation of SIMS at Stella Polaris AS, a prawn producer located in the northern part of Norway.

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1 Introduction

The world has gone through three major stages of industrial revolutions, each leading to significant changes in different aspects of manufacturing and bringing about huge benefits for humankind and societies. Now in 2010s, the world is welcoming Industry 4.0, known as the fourth Industrial Revolution and the Era of “Internet of Things”. Needs from customers in the market play a crucial role in the shifts of manufacturing paradigms. Personalization, developed from customization, is the new trend for the purpose of meeting every single customer’s need. Manufacturers in industries are facing challenging changes and need to cope with those challenges in order to be successful in the market and to gain competitive advantages.

1.1 Challenges for manufacturers

The general challenges for manufacturers come from changing customer demands and increasing market competition, the environment of industrial revolutions along with manufacturing paradigm shifts and progresses in technological and managerial approaches, etc. To be in a summary, manufacturers have been facing challenges mainly from the following two directions:

1) ***From customers and market***: The thinking nature of human as consumers and customers has been changing [6]. Customers have become more demanding for innovative products (goods and services) within shorter lead-time, at lower cost, and with better quality. These demands form the strategic focuses of market competition (i.e. market winner and market qualifiers [7]). Manufacturers are challenged to respond quickly to meet those needs from customers in order to survive from their competitors in the market.

2) ***From the industrial revolution or new manufacturing paradigm***: Under the circumstance of each industrial revolution, new manufacturing paradigms along with enabling technologies and supporting methodologies/methods (or in similar forms of philosophies, principles, techniques, tools, approaches, and models) have been emerging and evolving all the time, resulting in the existing ones becoming obsolete and replaced by new and innovative ones. Challenges occur when manufacturers try to adapt to the new trends, often associated with expensive costs and insufficient knowledge or skills.

1.1.1 A historical perspective of industrial revolutions

Ever since humankind began to make things in the form of products by hand (i.e. **manufacture** in early time) and exchange their **products** – goods or services (i.e. Barter), early **market** has formed based on the fundamental relationship between supply from suppliers and demand from customers, and market **competition** has arisen caused by more than one seller or one buyer. After commodity money was introduced to the market, **businesses** began to come into the form of providing goods or services in exchange for money instead of for other goods or services, aiming to gain a profit or surplus.

Following agricultural revolutions started the early Industrial Revolution (IR) in Great Britain in the first half of 18th century, which greatly increased the output of a worker owing to the inventions of machine tools such as the famous spinning jenny. James Watt’s steam engine accelerated the progress of the **1st Industrial Revolution** beginning from 1780s. Machines powered by steam or water further boosted productivity.

The advents of electricity, electrical telegraph, telephone, and railroads in the 19th century brought the industrial revolution into a new level. Ford's assembly line introduced in 1870 in America was often regarded as the start of the **2nd Industrial Revolution**, also known as the technological revolution.

The **3rd Industrial Revolution** began in the late 1960s and further automated production supported by electronics (e.g. programmable logic controller and computers) and information technology (IT). Toyota Production System developed in Japan in the mid-late 20th century, brought about advanced modern management philosophies.

In the early 2010s, the initiative of Industry 4.0 originated in Germany, indicating the beginning of the **4th Industrial Revolution**, with "a vision of integrated industry implemented by leveraging cyber-physical systems (CPS), embedded computing, and Internet of Things (IoT) technologies [8]".

1.1.2 A historical perspective of manufacturing paradigm shifts

Manufacturing is an important activity to provide human and society with necessities and the manufacturing industry promotes economic growth and social development for a nation. Over time, the manufacturing industry has evolved through several paradigms, subject to the level of industrialization and different technological and market conditions.

The first manufacturing paradigm was called "**Craft production**" [9]. In early time, craftsmen made products by hand that were specifically required by their customers using simple tools such as knives and wheels. The cost of products was relatively high and the production was not scalable due to geographical constraints of the craftsmen [9].

From the 18th century, more advanced manual tools and semi-manual/automatic machines were invented, such as John Kay's flying shuttle (1733), the spinning jenny (1764), and power looms in the textile industrialization. A selected history of some major developments during the early or first Industrial Revolution (from the 18th century to the mid-19th century) can be found in Table 1.

Due to urbanization and population shift after the 1st Industrial Revolution took place, large quantities of goods and services were in demand in populated areas. Market competition was not in a high degree at that time and only focused on cost since most people just wanted their basic needs covered as cheap as possible. The success in Ford's assembly line (1870), indicating greatly reduced the time it took to produce a car and lowered the price of a car, therefore urging other manufacturers also to improve their processes. Enabled by interchangeability, Ford's moving assembly lines (1913) and Taylor's scientific management (1909), the industry succeeded in "providing low-cost products through large-scale manufacturing", leading to the development of the manufacturing paradigm "**Mass production**" [9]. Mass production, sometimes known as flow production, is also one of the three conventional production methods, together with batch production and jobbing production (or one-off production) [10].

Manufacturers under the paradigm of mass production focuses all on the pursuit of productivity and neglected customer needs for variety. Henry Ford stated that "Any customer can have a car painted any colour that he wants so long as it is black". In the mid-20th century, the mass production paradigm was criticized by management gurus that it resulted in unfocused growth leading to the inefficient usage of resources in the organizations [11].

During the 1970s, Japanese products invaded the global markets with better quality yet still low cost. Globalization of markets made competition more and more intense. The focus of market competition shifted from cost to quality, giving rise to the development of total quality management for achieving continuous quality improvement. Toyota production system developed by Taiichi Ohno and his team in Toyota from 1950s to 1970s brought two remarkable philosophies, the “Just-in-time manufacturing” philosophy that initiated as a method to reduce inventory levels, and a similar but more generalised management philosophy “**Lean manufacturing**”, which can improve quality and productivity and reduce costs through the elimination of waste. Lean manufacturing is also described as a manufacturing paradigm [11] and often compared with that of agile manufacturing, which is mentioned below.

The manufacturing paradigms of “**Mass customization**” emerged in the late 1980s as customer demands for product variety increased [9]. The definition of mass customization is “providing tremendous variety and individual customization, at prices comparable to standard goods and services...with enough variety and customization that nearly everyone gets exactly what they want” [12]. Mass customization was enabled by some important concepts and technologies, including product family architecture, reconfigurable manufacturing systems, and delaying differentiation [9].

Influenced by the mass customization, the paradigm of “**Agile manufacturing**” was put forward in 1990s as a manufacturing strategy to address challenges caused by dynamically changing market conditions under globalization and rapidly changing customer needs for a variety of products. Agile manufacturing is a natural development from lean manufacturing, requiring organizations and facilities to become more flexible and responsive to customers instead of to emphasize on cost-cutting [13].

The beginning of the 21st century has witnessed the emerging of a new manufacturing paradigm which is called “Personalization” or “**Personalized production**”, driven by consumer’s desire to influence and participate in the design of products [9]. Unlike that manufacturers design basic product architectures and customers can select the preferable assembly combination in mass customization, customers can be involved in designing the products from the very beginning, in simulation and prototyping, and in the manufacturing processes, until finally provided with tailor-made products according to own preferences or specifications. That is to say, customers can participate in the entire product life cycle. This can be realized through close collaboration between manufactures and customers, which could be enabled by e.g., open product architecture, on-demand manufacturing systems, the Internet of Things, and responsive cyber-physical systems, which are proposed under Industry 4.0.

The globalization of the economy and the liberalization of trade from the end of the 20th century have formulated unstable conditions in the marketplace and intensive competition in the business environment [14]. Competition is getting more and more intense with respect to price, quality, selection, promptness of delivery and service, from the viewpoint of customers. These criteria are in the same meanings as and can be replaced by the terms – cost, quality, variety, responsiveness (lead-time and service) or customer experience, from the viewpoint of manufacturers or suppliers. Removal of barriers, international cooperation, and technological innovations further cause competition to intensify. Trends in global sourcing, continuously increasing competition, and more marketplace uncertainty become some of the drivers for popularizing the concept of “**Supply chain management**” (SCM) [15]. SCM is a management philosophy and involves the management of supply chain assets and product, information, and fund flows to maximize total supply chain surplus [16].

The competitive playing field has shifted from company versus company to supply chain versus supply chain. A company’s partners in the supply chain may well determine the company’s success, as the company is intimately tied to its supply chain [16]. As a consequence, closer coordination and relationships within a supply chain are necessary for a company to be more successful.

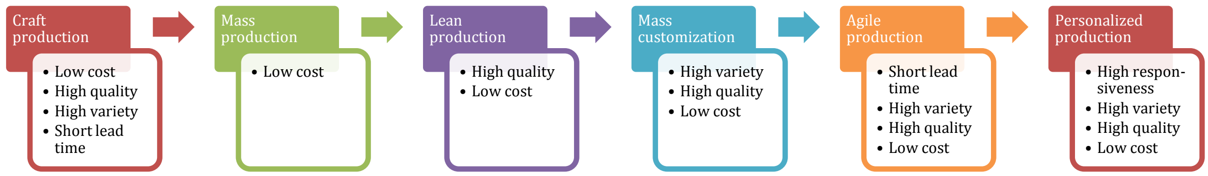

Figure 1 – Changes in the focus of customer needs or market competition under manufacturing paradigms.

Figure 1 summarizes the focuses of customer needs under different manufacturing paradigms. Under each paradigm, the focus of customer needs also form the focus of market competition, since manufacturers as suppliers compete with each other in meeting customer needs in order to be successful in the market and gain the competitive advantage. Fierce competition on a global level (more and more intense) and changing customer needs (more and more demanding) have been the major driving forces behind industrial revolutions and in the shifting of manufacturing paradigms, stimulating a rapid pace of innovations and bringing huge progresses in technology and market economy.

1.1.3 Industrial revolutions, changes, challenges, and innovations

While increasingly demanding and rapidly changing customer needs are the beneath reason that has driven industrial revolutions at different periods, these revolutions have brought to the world radical **changes** in diverse areas, caused huge **challenges** for industries and manufacturers, led to massive **innovations** and transformations, and remarkably affected people's way of life.

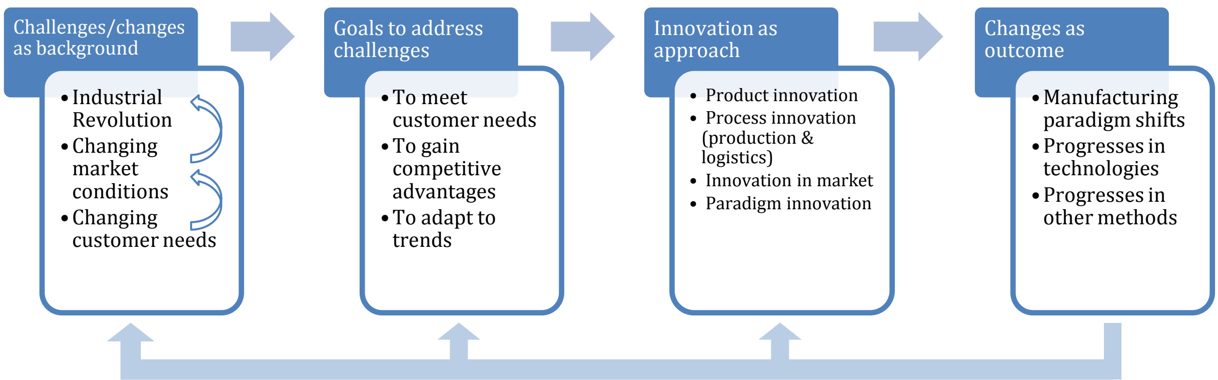

Figure 2 – A framework for identifying the relationships among changes, challenges, and innovations under the background of industrial revolutions.

Figure 2 suggests general relationships among changes, challenges, innovations, and industrial revolutions. **Changes** in needs from customers and market competition among suppliers stimulate changes in manufacturing industries, leading to the rise of industrial revolutions at different time. Meantime, these changes bring challenges for manufacturers in the industries.

In order to address the **challenges** caused by the changes, goals of a manufacturer targeting at each challenge are to meet customer needs, to gain competitive advantages from the market competition, and to adapt to new trends brought by each industrial revolution (e.g. new manufacturing paradigm, new technology, new managerial method, and also new customer needs).

To achieve the above goals, **innovations** as approach are called for. There are four types of innovation according to Tidd & Bessant [17]: product innovation, process innovation, position innovation, and paradigm innovation. Generally, product innovation can meet customer needs; product, process and position innovations can help manufacturers to gain competitive advantages in the market; and all types of innovation support with adapting manufacturers to the new era of industry.

Innovations result in more changes such as manufacturing paradigm shifts, progresses in technologies, progresses in managerial methods, etc. These changes are not only outcomes from innovations. They also open new opportunities for the current industrial revolution or bring new challenges and further promote a new industrial revolution (e.g. technology-driven industrial revolutions), forming loops of evolution over time. Manufacturers are urged to adapt to these progresses or shifts. Progresses in technologies and managerial methods also help manufacturers to overcome challenges. Integrating technological and managerial approaches contributes to strengthening the overall competence of manufacturers.

1.2 Challenges in NPA region

The Northern Peripheral and Arctic (NPA) region (as shown in Figure 3) bears abundant natural resources, including petroleum, natural gas, coal, other mineral resources, renewable energy, and fish resources. While the exploitation of resources provides undoubtedly a distinct opportunity for rapid economic and social development in the region, the increasing activities around the NPA region bring not only opportunities but also challenges in diverse areas such as borders and sovereignty, resource management, and environmental issues. These matters often need to be balanced among the Arctic states and across different industries and areas in order to achieve sustainable development for the region.

Figure 3 – The Northern Peripheral and Arctic (NPA) region [18].

For the manufacturing industry, manufacturers in NPA region are predominately small and medium-sized enterprises (SMEs: see more in Section 4.1.3). These SMEs face considerable challenges like inadequate exposure to international environment due to limitations commonly related to firm size, geographical isolation, standards/quality, supply chains/logistics, market opportunities, and technology innovation [5] – a lack of benefits that could otherwise be provided by industrial clusters.

In order to address these challenges and to become more competitive in the global market, new and innovative ways are to be sought for. Cooperation and collaboration are strongly called for among SME networks together with external organisations (such as research institutes or government departments).

The move towards sustainability, achieved through reduction in resource use and waste generation, also demands for an optimized structure of the supply chain in the manufacturing industry.

1.3 Summary

In this chapter, challenges for manufacturers in the manufacturing industry and challenges in the NPA region and specifically for SMEs in this region are discussed.

Challenges for manufacturers are mainly from two directions: changing customer needs (more and more demanding) and changing market conditions (more and more intense competition); and a new manufacturing paradigm and/or industrial revolution. These challenges or changes form loops that have been pushing the world forward:

1) changing customer needs (as shown in Figure 1) impact the focus of market competition and further drive an industrial revolution;
2) manufacturing paradigm shift and technological and other progresses through innovations come along with and also influence the industrial revolution (loops during the same IR); and
3) those progresses then again lead to more demanding customer needs and drive a new industrial revolution (a new loop for a new IR).

The evolutions of both industrial revolutions and manufacturing paradigm shifts have been described in detail from a historical perspective, relating the changing focuses of customer needs and market competition and some major technology development and managerial approaches. Customers demand products more than just at lower cost, with higher quality, and in shorter lead-time. Variety and service become rising factors under the manufacturing paradigm of customization and personalization Manufacturers are challenged to respond quickly to meet those needs from customers in order to survive from their competitors in the market.

Challenges for manufacturers in the NPA region (mostly SMEs) include inadequate exposure to international environment due to geographical isolation and often related to small firm size, and a lack of benefits that could be provided by industrial clusters such as logistics/supply chains, market opportunities, and limited access to new technology. Another arising challenge not limited to the NPA region, lies in sustainability, which can be achieved through efficient use of resources and reduction of waste. This, however, calls for an optimized structure of supply chains in the manufacturing industry.

In order to address these challenges and to become more competitive in the global market, cooperation and collaboration are strongly called for among SME networks together with external organisations (such as research institutes or government departments). Under the background trend of Industry 4.0 and the new manufacturing paradigm of personalization in the manufacturing industry, there has emerged many initiatives under R&D work from all over the world, attempting to develop new manufacturing methods to allow manufacturers to closely follow the current trends.

The relevant initiative proposed at UiT, Narvik, Norway in 2015 is called "Small-scale Intelligent Manufacturing System" (SIMS), in which the application and integration of technological approaches and managerial methods (or diverse methods) is highly emphasized [5].

The main purpose of this thesis project is to further develop the concept of SIMS. Based on a theoretical work, a case study is to be conducted regarding possible implementation of SIMS at the company Stella Polaris AS - a prawn producer in the Northern Norway.

2 Literature review on manufacturing system

In Chapter 1, the evolutions of industrial revolutions and manufacturing paradigm shifts have been described from a historical perspective. Changing focuses of customer needs and market competition have been discussed and a few major technology developments and management philosophies have been mentioned. Challenges caused by changes met by manufacturers at different periods have led to the evolution of the manufacturing industry and the development of manufacturing systems. When attempting to develop a new type of manufacturing system, it would be a wise idea to go through literature reviews on manufacturing and development of manufacturing systems so far. We begin from the definition of manufacturing and manufacturing system and try to cover most aspects of a manufacturing system. The emphasis of literature review will be on the progresses and trends in manufacturing methods in Chapter 3, including progresses and trends both in technological approaches (e.g. system techniques) and in managerial methods.

2.1 Definition of manufacturing system

There are many versions of interpretations for the term ***manufacturing*** [19]:

- *Originally from the Latin language*: make by hand;
- *Simply*: making things;
- *Economically*: the transformation of materials into items of greater value by means of one or more processing and/or assembly operations;
- *Technologically*: the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes assembly of multiple parts to make products.

Manufacturing processes can be generally seen as the transformation of inputs into outputs (e.g. in the form of goods or service). A ***system*** is a set of components that are connected/arranged in a way to perform a task or carry out a function in an environment, which fulfils a mission. The primary mission of a manufacturing system is to fulfil a customer request.

A ***manufacturing system*** (MS) receives inputs (raw material, knowledge, energy, human resources, etc.) and transforms those into a set of outputs over several processes [20]. The output sometimes in the form of material differs from the input material in a certain area that is meaningful or value-added. Aside from inputs, processes and outputs, manufacturing systems often have a fourth element: feedback (loop) - a way that enables the inputs or processes to be modified as a result of what happens at the output. In a manufacturing system, feedback can mean quality control checks that the products meets design specifications or feedback from customers and then adjusting the process to make sure it does. Manufacturing systems can be modelled with a system diagram, and controlled by visual, mechanical or electronic devices. Everyone/everything involved in designing and making products has a responsibility to minimise risk.

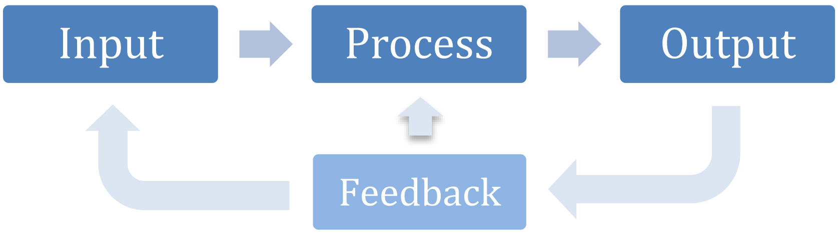

Figure 4 – A simple flowchart of a manufacturing system.

2.2 Basic components of manufacturing system

The essential components of manufacturing systems [21] are:

- ***Physical systems***: All physical aspects of a manufacturing system, including factories, facilities, machines, tools etc., raw materials, material handling systems, work in process, as well as products.
- ***Decision structures (or "operation")***: All aspects of decision structures that determine how the system functions, such as production planning (i.e. decisions on production).
- ***Information***: All data that will be accessed by some function/person/decision-maker/software/etc. and whose value may be used deciding upon an action. This includes design/machine/tool data, inventory status, process data, vendors/clients/personnel data, even data handling facilities (e.g. database management systems) and mechanisms that are required for the flow of information (i.e. information technology) including communication protocols (such as TCP/IP, ISO-OSI), etc.
- ***Humans***: All personnel, vendors, customers, etc. Customers are an essential human element in the design of a manufacturing system.

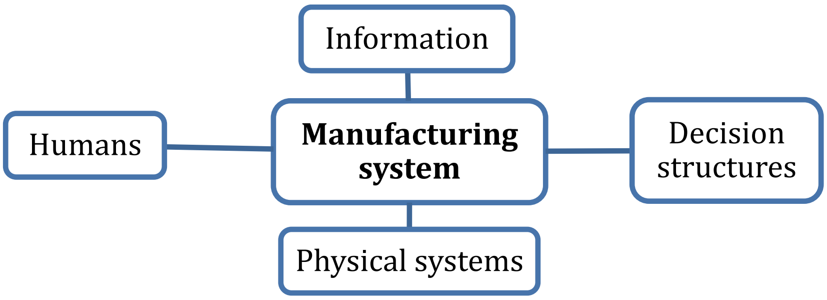

Figure 5 – Essential components of a manufacturing system [21].

The process of designing a manufacturing system therefore must engage upon the design of each of the above four components and focus on their integration in order to follow the trend in the industry.

2.3 Activities of traditional manufacturing systems

Manufacturing systems have been traditionally known as the integrated combination of various activities (or functions), such as design, process planning, production planning, quality assurance, storing and shipment, etc., as shown in Figure 6.

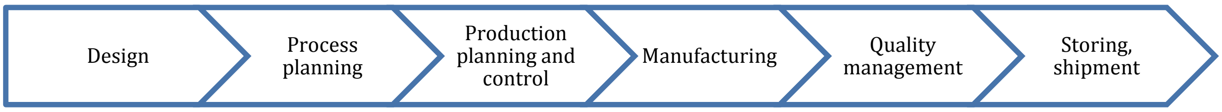

Figure 6 – Activity components of traditional manufacturing systems [20].

The term "activity components" is used from a functional view to replace the original "components" used in [20], to differ it from "components" in Figure 5 from a structural view when decomposing a manufacturing system. Detailed descriptions on each of the activities above and their sub-activities can be found in [20]. The set of activities within each function should be managed carefully in order to create a successful manufacturing environment.

The above process is quite simplified. It does not include activities such as prototyping, procurement, sales and marketing. Besides, the management activity is limited to quality management. Under the trend of simulation, prototyping, business management, supply chain management, and so on, the manufacturing system needs to be reconstructed.

2.4 Types of manufacturing process

Process planning includes the selection of processes, equipment and tooling, and the sequencing of operations required by the design process [20]. Defining the type of manufacturing process or environment is important for manufacturing related decisions.

Conventionally, manufacturing can be divided into three major categories [10]:

- ***Flow or mass production***: producing a limited range of products in high volume.
- ***Batch production***: producing a much larger product ranger than flow manufacturing, but the products tend to have lower volumes and repeat orders are expected.
- ***Jobbing or one-off production***: producing “one-offs”, i.e., there is no expectation that there will be repeat orders for the products, and characterized by a high product-type range but a low volume.

Another categorization has five manufacturing categories across all manufacturing environments. Most manufacturing processes fit into one of five general categories [22]:

- ***Discrete (or Project)***: This manufacturing environment is highly diverse, covering a range from few to frequent setups and changeovers. Products also range from being very alike or highly disparate.
- ***Job shop***: Job shops rarely have production lines. Instead, they have production areas. These areas may assemble only one version of a product, a dozen or even dozens of versions. When demand grows, the operation is turned into a discrete line, and selected labor operations can be replaced by automated equipment.
- ***Process – batch***: Design considerations are analogous to those of “Discrete” and “Job shop”. The disciplines are more diverse. It can take only one batch or several batches to meet demand. In some instances, batch processes can be continuous in nature, making one batch after another of the same product.
- ***Repetitive flow***: This manufacturing environment mostly has dedicated production lines that turn out the same item, or a closed related group, 24/7 all year long. The speed of operation modulates differences in customer demands. There is little setup or changeover activity.
- ***Process – continuous flow***: Design considerations are analogous to “Repetitive flow”. They run 24/7 all the time. The disciplines to create final product and production process are more diverse. The main difference is that production materials are gases, liquids, powders, or slurries.

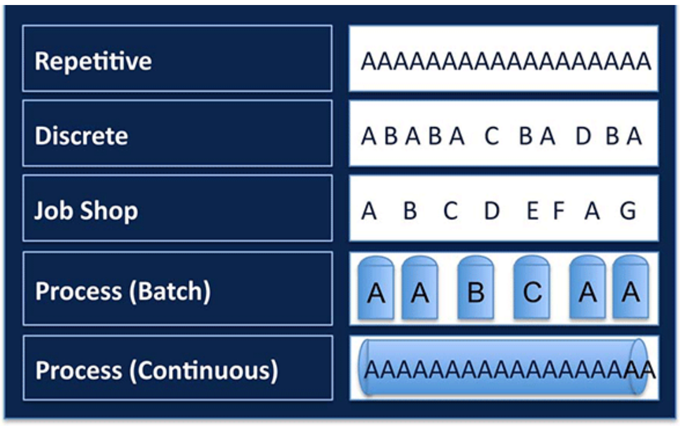

Figure 7 – Five types of manufacturing processes [22].

To get products out of the door, most companies use a combination of more than one of the above environments. This is especially true considering today’s use of the supply base versus the historical practices of vertically integrated companies [22]. Figure 8 shows the link between the volume-variety relationships and the five types of manufacturing processes (with slightly different names but the same meanings as in Figure 7).

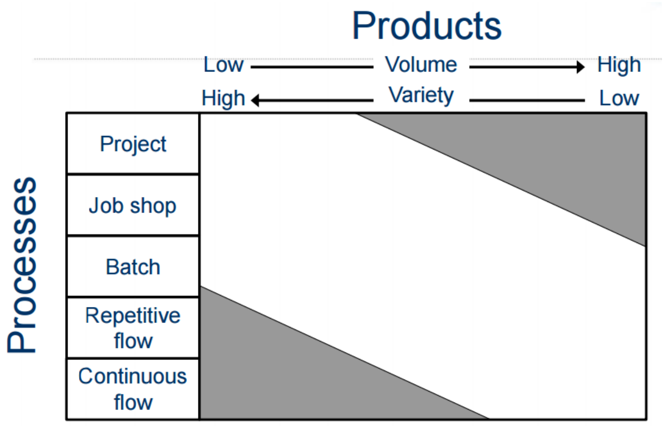

Figure 8 – Linking manufacturing processes with production volume and product variety [23].

The current **trend** of manufacturing process type influenced by the new manufacturing paradigm of personalization is **one-piece manufacturing**, similar to single product, project or one-off production. Batch and job shop are intermittent manufacturing (although batch processes can be continuous in some meanings), repetitive flow and continuous flow are both flow manufacturing.

2.5 Types of manufacturing interaction strategy

The three manufacturing strategies in practice are [24]:

- ***Make-to-Stock (MTS)***: The production process allows the manufacturer to complete the products before an order receipt from the customer. Customer orders can be filled from the existing stocks. This type of manufacturing strategy is suitable for flow manufacturing process.
- ***Assemble-to-Order (ATO)***: The receipt of order will initiate the assembly of products. All the components used in the assembly, packaging or finishing process are planned and stocked in anticipation of an order from a customer.
- ***Make-to-Order (MTO)***: The receipt of an order triggers planning to finish the items to the specifications of the customer. The final product is usually a combination of standard items and items customized to meet the special needs of the customer.

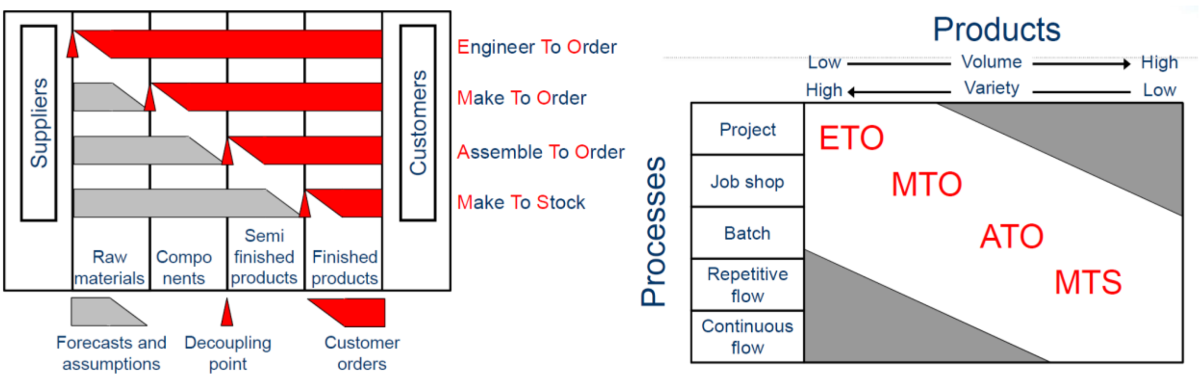

Figure 9 – Linking manufacturing strategies (left) with production volume, product variety and manufacturing processes (right) [25].

A more trendy manufacturing strategy is:

- ***Engineer-to-order (ETO)***: The product is engineered and developed only when the customer places an order. Suitable for the manufacturing process type of "Project" in Section 2.4.

Figure 9 illustrates the four manufacturing interaction strategies with customer order decoupling points – CODPs (left) and shows the link among manufacturing strategies, processes, and volume-variety relationships (right).

2.6 Types of manufacturing layout

Traditional types of manufacturing layout include [26]:

- ***Fixed position layout or Project layout***: Personnel, equipment, tools, materials, and so on are brought together to the project. This type of layout design is suitable for the manufacturing process type of "Project" in Section 2.4.
- ***Functional layout or Process layout*** *(or Job shop)*: All machines or workstations with a similar function are grouped together, often in the same department. Suitable for the manufacturing process type of "Job shop".
- ***Product layout*** *(or Flow shop)*: I-shape (linear) or U-shape setup of machines is utilized to produce one product group. Suitable for flow manufacturing with standardized products and high production volumes.
- ***Cellular layout***: A group of different machines are put together to perform complete production of a family of similar parts. It is an equipment configuration to support cellular manufacturing and also a compromise between process layout and product layout.

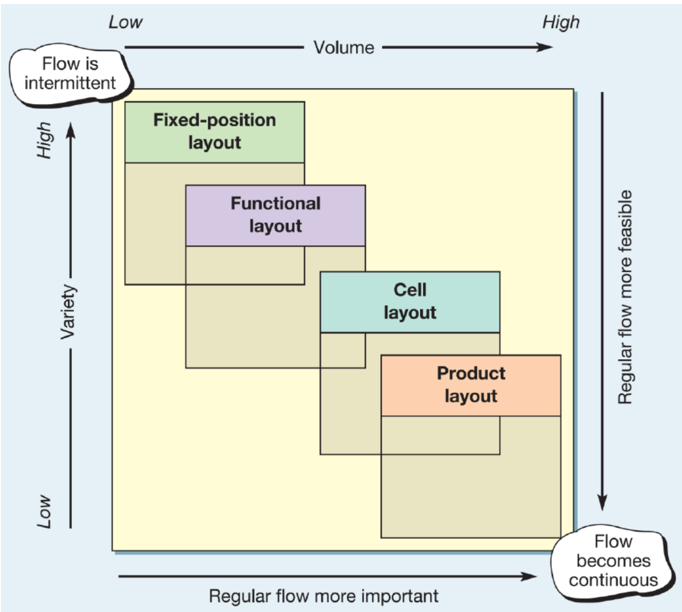

Figure 10 – Linking manufacturing layouts with production volume and product variety [26].

Figure 10 shows the link between the volume-variety relationships and four types of manufacturing layout design. ***Automated production line*** *(transfer machine)* has been one **progress** in influencing manufacturing layout design It consisting of a series of workstations connected by a transfer system (e.g. conveyors) to move parts between the stations.

The newest **trend** in transforming manufacturing layout design is **digital factory or virtual factory**. The concept of digital factory is the mapping of all the important elements of the enterprise processes by means of information and communication technology (ICT) [27]. A virtual factory is defined as an integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability [28].

2.7 Levels in manufacturing system

There are many studies relating the levels of a manufacturing system leading to different ways of division. A very common way is that manufacturing systems are divided into four levels [29]:

- ***Enterprise***: a system that has its own independent management;
- ***Shop floor***: a sub-system of an enterprise where manufacturing activities are carried out;
- ***Cell or line***: a group of machines that produce a part; (this level is omitted when there are only three levels);
- ***Machine***: a single entity that changes the input material.

Cheng et al. pointed out in [30] that general manufacturing systems can be decomposed into seven levels of decision hierarchies according to Rogers et al. in 1992.

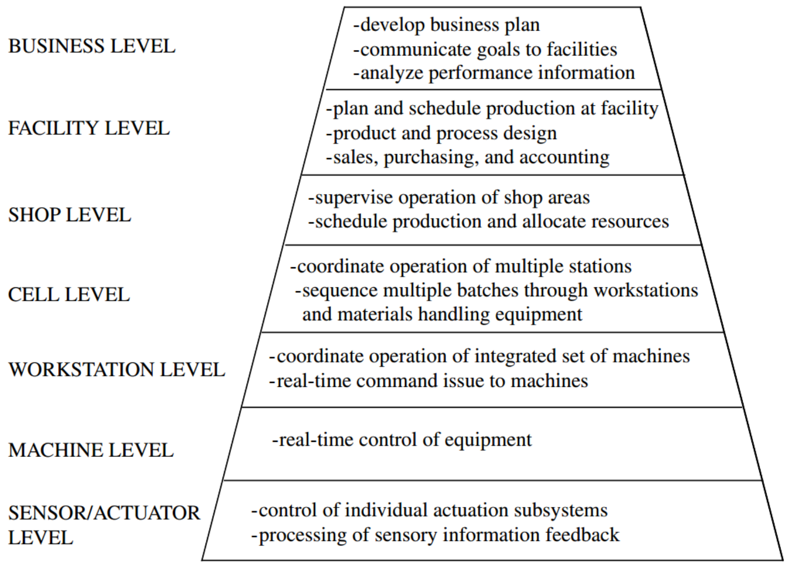

Figure 11 – A seven-level manufacturing hierarchy [30].

2.8 Summary

In this chapter, a literature review is conducted mainly regarding the concept of manufacturing system (MS). The discussion covers the following areas:

- definition of MS;
- basic components and activities of MS;
- types of manufacturing process; interaction strategy; and layout design;
- levels in MS.

Although the discussion gives a clear idea of what a manufacturing system covers, many aspect should be updated as manufacturing systems are evolving all the time due to for example market competition and technological progresses. A modern structure of manufacturing system needs to be developed.

3 Literature review on manufacturing system methods (historical perspective)

In Chapter 2, a literature review on the concept and relating aspects of a generalized manufacturing system is conducted. Due to several factors such as changes in market conditions and customer expectations and requirements, innovative technology and methods have been continuously sought for to deal with those changes and challenges faced by manufacturers, driving frequent emergences of new types of manufacturing systems. In this chapter, the focus is on the changes or progresses and trends in manufacturing methods from a historical perspective, including both technological approaches (e.g. system techniques) and managerial or other methods for manufacturing systems.

3.1 Changes in machining/manufacturing process methods

Before discussion, we differentiate the meanings of machining and manufacturing. Manufacturing is "the industrial activity that changes the form of raw materials to create product", while machining is defined as "the removal of the unwanted material (machining allowance) from the workpiece, so as to obtain a finished product of the desired size, shape, and surface quality" [31]. This definition of machining emphasizes too much on the removal of materials, which could be out of date due to the emergence of many additive techniques. Generally, machining is one of the means in manufacturing with the aid of machines.

3.1.1 Removal machining

In very early time, humankind began to adopt the removal machining method through cutting techniques using simple tools made from bone, stick, or stone (Stone Age), later replaced by bronzed (Bronze Age) and iron (Iron Age) tools. Water, steam (1st IR), and later electricity (2nd IR) power were used to drive tools in metal cutting machines (**machine tools**). A machine tool is a machine for shaping or machining metal or other rigid material, usually by cutting, boring, grinding, shearing, or other forms deformation. Machine tools are designed to achieve the maximum possible productivity and to maintain the prescribed accuracy and the degree of surface finish over their entire service life [31]. More about machine tools and removal machining technology can be found in [31].

3.1.2 Subtractive manufacturing and formative manufacturing

Subtractive manufacturing process is a manufacturing process of shaping components that involves material removal [32]. Subtractive manufacturing can be regarded as a later version of saying of removal machining. The term is mostly used for removal machining method with the application of numerical control (NC) machines (from 1950s) and computerized numerical control (CNC) machines during the 3rd Industrial Revolution.

In subtractive manufacturing processes, the block of material that is larger than the final size of the desired part is gradually removed until the desired shape is achieved, using machining processes such as milling, turning, drilling, planning, sawing grinding, EDM (electrical discharge machining), laser cutting and water jet cutting [32].

Another traditional manufacturing process is formative manufacturing process that shapes components through compression or consolidation process, with the application of pressure including forging, pressing and bending [32]. Both formative manufacturing and subtractive manufacturing waste a lot of materials, time, and energy.

3.1.3 Additive manufacturing

Additive manufacturing is defined as the "process of joining materials to make objects from 3D model data, usually layer upon layer" [5]. Many additive techniques has appeared since 1980s or 1990s, allowing manufacturers to adapt to the emerging manufacturing paradigm of mass customization at the time. These techniques including 3D printing, stereo lithography apparatus (SLA), selective laser sintering (SLS), fused deposition modelling (FDM), laminated object manufacturing (LOM), ballistic particle manufacturing (BPM), solid ground curing (SGC), etc. [5]. Additive manufacturing (as the umbrella term for those relevant techniques) technology has become matured in the decade of 2000s and enabled to construct components with complex geometries by means that are not easy to produce using conventional removal machining methods.

Additive manufacturing technology opens up the possibility of rapid prototyping and manufacturing (RP&M), which can be used to produce customized product with mass production efficiency [32]. Additive manufacturing process is able to reduce the lead-time or time-to-market required for introducing a new product and meantime reduce the material usage.

3.1.4 Hybrid manufacturing

Hybrid manufacturing process has been under research studies by the early 2010s. A hybrid process refers to "the combination of an additive and subtractive process, sequential or integrated, including planning for fixturing and orientation in the quest of a final, usable part" [33]. As an integrated approach, hybrid process allows component fabrication by additive process and surface finishing by CNC (subtractive process) to be achieved in a single setup, and allows different compositions of materials to be used in the same component also [34]. Changeover from additive to subtractive simply requires a tool change and can be achieved fully automatically.

3.2 Changes in manufacturing system paradigms (technological approaches)

There are many breakthroughs in technology continuously taking place and contributing to the development of manufacturing systems along time. Several major technologies/techniques that have been leading fundamental changes in manufacturing are listed below under three major categories [5]:

1) Artificial intelligence (AI) technology:
    - Computer technology & computing techniques;
    - Computer-aided systems (software-based) – CAD/CAM, ERP, etc.;
    - Cognitive technology;
    - Robotics techniques – industrial robots, etc.;
    - Virtual techniques; etc.
2) Manufacturing technology:
    - CNC/NC machines (additive manufacturing);
    - 3D printing (additive manufacturing);
    - Reconfigurable machine tools; etc.
3) Information and communication technology (ICT):
    - Computer network – Internet (including a communication protocol);
    - Information space – World Wide Web (WWW or the Web);
    - Agent technology;
    - Mobile technology;

- Cloud technology;
- Internet of Things;
- Big Data; etc.

Technological progress is both the major outcome driven by manufacturing paradigm shifts (mainly four: from craft to mass production to mass customization to personalization) and the most significant impact and enabler on the development of manufacturing system paradigms. Technological development enables manufacturing methods to transform from manual tools, to semi-automatic machines, to automated and computer-integrated, intelligent and autonomous manufacturing systems [35], as shown in Figure 6, Figure 12, Figure 14, and Figure 15.

3.2.1 Traditional manufacturing: manual or semi-automatic machines

In the early Industrial Revolution, Richard Arkwright who invented water frame in 1767 also ushered the factory system. As the beginning of the 2nd Industrial Revolution, Henry Ford developed one of the earliest assembly lines. Before the 1st World War broke out, there had emerged a lot of inventions on tools, machines or manufacturing systems in the earlier form, from manual tools, to semi-manual or semi-automatic machines, to full automatic machines (information technology not used yet). Table 1 lists some major inventions of tools or machines from the early 18th century to the end of 19th century (during the 1st and 2nd IRs), mainly in the textile industry.

3.2.2 Automated manufacturing system

The concept of manufacturing system was not matured until the 3rd Industrial Revolution when automation became the key objective and feature. Draper Labs defined an automated manufacturing system (AMS) in 1983 as:

- "A computer-controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one part number at low to medium volumes" [10].

Different from automatic machines developed in the late 19th century or in the early 20th century, the invention of programmable logic controller (PLC) in 1969 and the development of information technology (IT) further promoted automation in manufacturing and facilitated automated manufacturing systems or lines. The invention of computers and rapid improvements in its hardware and software contributed largely to the emerging of CNC machines and industrial robots since 1960s.

3.2.3 Flexible manufacturing system

Flexible manufacturing systems (FMS) are often considered as a part of automated manufacturing systems [36]. The idea of FMS was first proposed in Britain in the early 1960s under the name "System 24", and the first physical system was implemented in the USA around the 1970s [37]. FMS can be regarded either as a manufacturing technology or as a philosophy, and has been developed in responding to the new strategy – customizability – from the changing customer need and in order to gain competitive advantage in the intense market competition [38]. The definition of FMS according to Groover [39] is:

- "A FMS consists of a group of processing stations (usually NC machines) connected together by an automated work part handling system. It operates as an integrated system under computer control."

The above definition indicates the three basic components of FMS: workstations, automated material handling and storage system, and computer control systems. FMS is capable of processing a variety of different part types simultaneously at the various workstations, and quantities of production can be adjusted in response to changing demand patterns. Different approaches to flexibility (manufacturing, operational, customer, strategic, and capacity) and three levels of manufacturing flexibility are explained in the book by [38].

3.2.4 Computer-integrated manufacturing

The concept of computer-integrated manufacturing (CIM) was first introduced by Joseph Harrington in 1979 and became popular until about 1984 [40]. While computer control plays an essential role in the development of automated and flexible manufacturing systems, computers also support many other functions in the manufacturing processes, including but not limited to those shown in Figure 12. Systems of computer-aid design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), computer-integrated manufacturing (CIM), computer-aided process planning (CAPP), computer-aided quality control (CAQC), automated storage and retrieval (AS/R) systems and automated guided vehicles (AGV) have been constantly developed and improved with the help of computing systems [20]. Effective utilization of computers in manufacturing has created numerous advantages. Figure 12 shows the basic process in a computer-integrated manufacturing system.

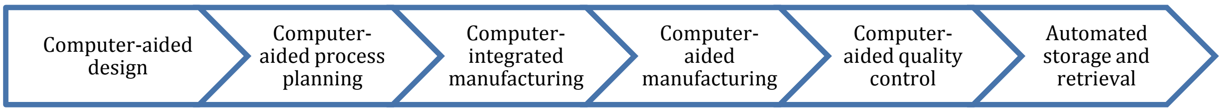

Figure 12 – Basic process in a computer-integrated manufacturing system [20].

Developments in computing systems did not only create considerable progresses in performing the respective functions but also made information systems capable of integrating manufacturing functions as well [20], facilitating overall integration in a manufacturing system. An earlier definition of CIM by Kochan & Cowan in [41] which is viewed as not putting much emphasis on the role of information is:

- "The concept of a totally automated factory in which all manufacturing processes are integrated and controlled by a CAD/CAM system. CIM enables production planners and schedules, shop floor foremen, and accountants to use the same database as product designers and engineers."

The Digital Equipment Corporation (DEC) gives the following definition of CIM:

- "CIM is the application of computer science technology to the enterprise of manufacturing in order to provide the right information to the right place at the right time, which enables the achievement of its product, process and business goals." [42] & [40]

The importance of information in a manufacturing enterprise is pointed out in this definition, but the definition does not emphasize much on the very important concept of integration. The next sub-section (3.2.5) describes integration in a manufacturing system separately.

A later definition of CIM stressing the importance of integration is given by the Computer and Automated Systems Association of the Society of Manufacturing Engineers (CASA/SME):

- "CIM is the integration of the total manufacturing enterprise by the use of integrated systems and data communication coupled with new managerial philosophies that improve organizational and personnel efficiency." [43]

Different definitions of CIM emphasize on different aspects. CIM can be an organizational structure, a strategic tool, a manufacturing approach/method, or an operating philosophy, etc., from different viewpoints of researchers at different time.

3.2.5 Integrated manufacturing

Faced by challenging changes, manufacturing organizations are required to cope with those in order to be successful and gain competitive advantage. This makes overall integration of manufacturing functions from design up to product shipment necessary. This integration is facilitated through information technology networks with respective information management systems. Figure 13 shows the basic functional components of an integrated manufacturing system. Integration brings different functions of an enterprise together into a unified system through computational intelligence.

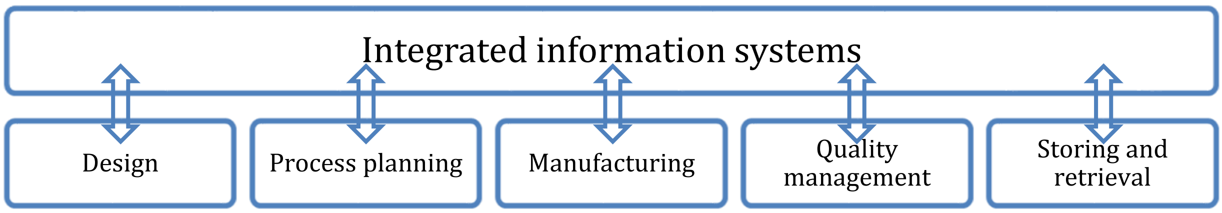

Figure 13 – Basic functions of an integrated manufacturing system [44] & [20].

All of the above four terms, AMS, FMS, CIM and integrated manufacturing, describe a highly automated and integrated manufacturing facility/cell with flexibility in operations. These terms can more or less be interchangeably used under many instances.

3.2.6 Intelligent manufacturing system

Intelligent manufacturing systems (IMS) are those performing the manufacturing functions as if the human operators are doing the job [44]. Intelligent manufacturing systems utilize artificial intelligence (AI) technologies/techniques for manufacturing activities in order to perform their intended functions. They can exhibit all characteristics of intelligent systems such as learning, reasoning, decision-making, and so on [20]. Figure 14 shows the basic process in an intelligent manufacturing system.

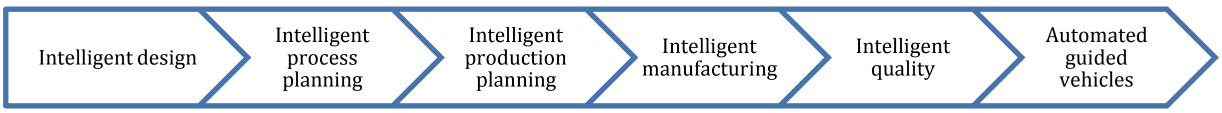

Figure 14 – Basic process in an intelligent manufacturing system [20].

IMS is also widely known as the name of an international organization devoted to developing the next generation of manufacturing and processing technologies during the 3rd industrial revolution.

3.2.7 Holonic manufacturing system

The concept of holonic manufacturing sytems (HMS) was proposed in 1994 by the HMS consortium [45]. A holon is defined as "an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects" [46]. A holonic manufacturing system consists of such autonomous and self-reliant manufacturing units (i.e. holons) which operate in a flexible hierarchy [47]. The definition of HMS by Shen & Norrie [45] is:

- "A holarchy which integrates the entire range of manufacturing activities from order booking through design, production and marketing to realize the agile manufacturing enterprise".

Holonic manufacturing was introduced as a new manufacturing paradigm to address the challenges caused by the need for low-volume and high-variety products from consumers [48], while agent technology can be regarded as a key technology for realizing the information processing of HMS [47].

Holonic manufacturing was one of the six IMS test cases which was set up in the early 1990s [48], and HMS is regarded as the most remarkable concept among IMS's [49].

3.2.8 Autonomous manufacturing system

The concept of autonomous manufacturing systems is believed to be first proposed by Baldwin & Raleigh [50] and has been developed since then. In this work, AMS II is used as an abbreviation of autonomous manufacturing systems, to distinguish it from AMS that stands for automated manufacturing systems. Autonomation is also described as "smart automation" or "automation with a human touch" from the Japanese word "Jidoka" that is a conceptual pillar of Toyota Production System.

The conventional manufacturing systems, such as the above-mentioned FMS and CIM, are unable to adapt to the complexity and the dynamic of the manufacturing environment. These systems use the pre-instructed programs to activate the automatic operations, and they should be stopped to reprogram and replan in the case of disturbances [49]. In order to improve the flexibility of the FMS, the agent technology is applied. Such agent-based FMS and agent-based HMS can adapt to the changes of the manufacturing environment. However, these systems only achieve greater efficiency if the agents are equipped with cognitive capabilities that improve the autonomous behaviors of the agents. A cognitive factory was proposed by Zaeh et al. [51]. In a cognitive factory, each machine and its process are equipped with cognitive capabilities like human behaviors, which enable factory environments to react flexibly and autonomously against the changes [49].

An autonomous manufacturing system has smarter and more autonomous agents (called "cognitive agents") than traditional agents in terms of operation scope. Cognitive agents are built based on the beliefs-desires-intentions (BDI) architecture and have intelligence other than autonomous and communicable characteristics. Intelligence is the ability of the agent to use its knowledge and reasoning mechanisms for making a suitable decision with respect to the environmental changes [52].

All the resources in an AMS II are modeled as intelligent entities with the abilities of identification, data collection, and autonomous decision making for adapting to disturbances. All the functions are designed to be autonomous.

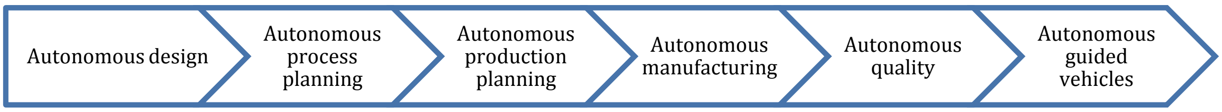

Figure 15 – The processes of an autonomous manufacturing system [20].

3.2.9 Reconfigurable manufacturing system

To overcome the limitations of flexible manufacturing systems, the idea of reconfigurable manufacturing systems (RMS) has been put forward since 1995. RMS allows flexibility not only in producing a variety of parts, but also in changing the system itself. A reconfigurable manufacturing system is designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components (e.g., machines and conveyors for entire production systems, mechanisms for individual machines, new sensors, and new controller algorithms) [53]. New circumstances may be changing product demand, producing a new product on an existing system, or integrating new process technology into existing manufacturing systems.

The key characteristics of RMS include modularity, integrability, convertibility, diagnosability, and customization [53].

The concepts of HMS, AMS II, RMS, and IMS are closely interrelated and emphasize on the characteristics of autonomy and intelligence of the system which contributes to agile manufacturing, with each concept emphasizing on different areas. HMS and AMS II are often interchangeably used, while IMS is a wider concept that includes HMS, AMS II and RMS.

Relationships among the concepts of intelligence, autonomy, reconfiguration/reconfigurability, and agility in manufacturing systems are explained in different literatures:

1) Reconfiguration and autonomy are criteria for adapting to the disturbances intelligently and effectively [49];

2) The two key characteristics of any system aimed at operating in a dynamic environment should be *Agility*, i.e. the ability to rapidly change the system behavior in response to, or in anticipation of changes in its environment and *Autonomy*, i.e. the ability to decide when and how to change the system behavior without waiting for external instructions [54];

3) Agility is more like a business philosophy for an entire enterprise, while reconfigurability deals with the responsiveness of the manufacturing system to new market opportunities and is one aspect of agility [53]. According to Wiendahl et al. [55], reconfigurability is an operational ability, flexibility is a tactical ability, and agility is a strategic ability. Each is a type of changeability (or flexibility when it is generally used) contributing to the responsiveness of the manufacturing systems.

3.2.10 Direct digital manufacturing

Direct digital manufacturing (DDM) describes the usage of additive manufacturing technology for production or manufacturing of end-use components [56]. While this definition focuses too much on the application of additive manufacturing, a more general definition of DDM is “an interconnection of additive manufacturing equipment, computers through a network (e.g. Internet and servers) and computer software” [57].

DDM takes advantage of the geometric complexity capability of additive manufacturing techniques to produce parts with customized geometrics [56]. Additive manufacturing technology opens up the possibility of rapid prototyping and manufacturing (RP&M). The integrating systems of CAD/CAM and RP&M highly improve the capability of rapid product development [5].

DDM has become a trendy manufacturing technology or method since 2010s, allowing for personalized production with the batch size of one and delivering personalized products in short lead time. Moreover, DDM has not only the possibility of combining advantages from the previous manufacturing paradigms (craft production, mass production, and mass customization) but also has a positive impact on sustainable development [57].

3.2.11 Cyber-physical system

The term of cyber-physical systems (CPS) is defined as “a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities” or “transformative technologies for managing interconnected systems between its physical assets and computational capabilities” [58].

CPS is a key enabler for future development towards transforming the manufacturing industry to the next generation of Industry 4.0, through developing the ability (of the cyber world) to interact with and expand the capabilities of the physical world through computation, communication, and control [58].

Within CPS, information from all related perspectives between the physical factory floor and the cyber computational space is closely monitored and synchronized [59]. Networked machines and products, though utilizing self-resilient ability and advanced analytics capability, and people in value networks, through real-time information and communication, will all be able to perform more efficiently and collaboratively

Interesting and trendy research tops in surrounding areas include design and development of next-generation (NextGen) aircrafts, vehicles (gas-electric hybrid buses), fully autonomous urban driving (e.g. wireless bus stop charging), renewable energy (e.g. bioenergy), biomedical and E-healthcare systems, etc. [58], aiming at creating better living environments for human being while taking care of the environment. Networking is the key trend in almost all areas.

As a summary and a supplementary of contents from Section 3.2.2 to Section **Error! Reference source not found.**3.2.9, Table 2 lists major developments in manufacturing systems from 1960s to the present (during the 3rd IR and the happening 4th IR).

3.2.12 Summary

A historical overview of the evolutions of machining/manufacturing systems has been conducted in this section (3.2) and in Table 1 and Table 2. However, it is not often easy to clearly distinguish various concepts due to reasons such as:

1) Those that emerged around the same timeline are often closely related and similar with each other regarding their backgrounds/challenges, definitions, and characteristics.

2) Each concept has been popular for a period or is still a hot topic now.The concepts have been developed along time, enabled by new technologies and/or methodologies. They can have several versions of definitions proposed by different researchers from different viewpoints at different time. In this work, the most popular and cited definitions are referred to.

3) Since newer concepts for manufacturing systems are often developed based on the previous ones, they also possess the same characteristics (those from the benefit side) as those of the older ones and possibly add some new features. The columns of "Major feature" in Table 1 and Table 2 present the most significant new feature that the new concept puts forward. This also applies to enabling technologies and methods in some degree. Some technologies have been existing and developed over time and some just became outdated.

Nevertheless, each concept has had a specific area to emphasize on. The work performed in this thesis project is based on an extensive literature review, drawing opinions from earlier researchers and then proposing a relatively structured and detailed overview. Such a work contributes to the development of a new type of manufacturing system.

Note that the numbers of the years listed in Table 1 and Table 2 are the emerging times of the corresponding concepts. They can be, for example, the time of the concept being introduced, the time of the technology being invented or patented, the time of the facility being designed or built, etc., depending on different cases and available information from literatures or some websites.

Table 1 – Major development in machines from the early 18^{th} century to the end of 19^{th} century.

IR	Progress	Emerging time	Challenge faced	Example	Implication	Contribution	Major feature	Limitation	Major driver / Enabling technology
Early Industrial Revolution in textile manufacturing	Manual tools	The early 18^{th} century	Human motivation to be more productive	Flying shuttle (John Kay, 1733)	Speeded up the hand process Could be mechanized, allowing for automatic mechanical looms	• Reduced the amount of labor work needed • Reduced the overall cost • Shortened time • Greatly increased productivity • Increased efficiency	Productivity	Heavy, noisy, and energy-inefficient; limited speed	Human/hand power
		From 1760s to between 1820s-1840s	Increase in weaving production due to the flying shuttle exceeded the capacity of the spinning industry.	Spinning jenny (James Hargreaves, 1764)	Speeded up the spinning process Reduced the amount of labor work needed			Low product quality (yarn not strong; coarse thread)	
	Semi-manual machines / machine tools			Water frame – water-powered spinning frame (Richard Arkwright, 1767)	Improved quality (stronger and harder yarn) *Ushered the **factory system**			Could spin only one thread at a time	Water power Cast iron technology
				Spinning mule (Samuel Compton, 1779)	*Combined the spinning jenny and water frame into one			Unsmooth driving motions	
			More metal parts required in textile mechanization created needs for machine tools.	Boring machine (John Wilkinson, 1774)	*Called the first machine tool Could bore cast iron cylinders such as for stream engines			Low accuracy	
1^{st} IR	Semi-automatic machines – water & steam powered		Production (cotton) could not keep up with demand in the textile industry. Process needed to be improved.	**First mechanical/power loom** (Edmund Cartwright, 1784)	*Often regarded as the beginning of the 1^{st} Industrial Revolution			Inherent dangers in the machines	**Steam power** - Steam engine (James Watt, 1781)
				Mechanical cotton gin (Eli Whitney, 1794)	Speeded up the process of removing seeds from cotton fibers			For specific use	
				Lancashire Loom (James Bullough &William Kenworthy, 1842)	*Semi-automatic power loom Self-acting			Had to be stopped to recharge empty shuttles	
2^{nd} IR	Automatic machines / assembly lines – powered by electricity	From between 1840s-1870s to 1914	Large demand for goods and services in the market **Mass production**	First assembly line in the meatpacking industry / slaughterhouse (1867)	*Regarded as the beginning of the 2^{nd} Industrial Revolution *Popularized mass production		Efficiency	Exactly the same product to any customer	**Electrical power** - Electromagnetic generator (Michael Faraday, 1832) - Electric motor (1870s)
				First assembly line in the automotive industry (Henry Ford, 1870)					
				Northrop Loom in the textile industry (1895)	*Fully automatic power loom Could be worked in larger numbers		Automation	Suitable for coarse thread but for fine cotton	Conveyor belts

Table 2 – Development in manufacturing system paradigms as technological approaches from 1960s to 2010s.

IR	Progress	Emerging time	Challenge faced	Concept implication	Contribution	Major feature	Limitation	Enabling technology/driver
3rd Industrial Revolution	Automated manufacturing system	1960s	Large demand for goods and services	Designed to efficiently manufacture more than one part number at low to medium volumes [10]	• Production as efficient as possible as cheap as possible • Increased productivity • Reduced the lead time • Reduced labor costs • More efficient use of equipment • Improved product quality	Automation	Unable to adapt to the complexity and dynamic of the manufacturing environment	Computer (in the early to middle 20th century) NC machines (1954) CNC machines and industrial robots (1960s) Programmable logic controller (1969) Automated material handling systems
	Flexible manufacturing system (FMS)	1960s-1970s	In response to changing customer demands	Capable of processing a variety of part styles simultaneously, with changeable volume and mix, on the same system [60]		Flexibility	High cost; unable to change the system itself (flexibility limited in operations)	
	Computer-integrated manufacturing (CIM)	1979	Market competition on quality	Integration of functions in the manufacturing processes supported by computers and information systems		Integration	Integration began at the operational level (Later also in business / management processes)	Computer-controlled machines (1960s) Computer and computing systems - CAD, CAM, CAE, CIM, CAPP, CAQC, AS/R systems, AGV, etc. Information technology (IT)
	Intelligent manufacturing system (IMS)	Early 1990s	**Mass customization** Consumer need for product variety	Capable of performing the intended manufacturing functions as if the human operators are doing the job (Kusiak, 2000)		Intelligence	Not quite suitable for personalized customization; requiring even shorter lead time	Artificial intelligence (AI) technologies - Multi-agent technology - Distributed AI
	Holonic manufacturing system (HMS)	Early 1990s	System need to adapt to rapid changes / disturbances Need to replace automation with autonomy and intelligence	Can adapt to the changes of the manufacturing environment (or overcome the disturbances) autonomously to realize the agile manufacturing enterprise	• Increased the productivity • Reduced the downtime • Reduced the cost of products	Autonomy	Can only achieve a greater efficiency; flexibility from the cognitive capability of human is missing	Agent technology – reactive agents Holons (autonomous, self-reliant, communicative & cooperative features)
	Autonomous manufacturing system	Early 1990s		Inherit the advantages of both automated systems and cognitive capabilities of human, enabling factory environments to react flexibly and autonomously against the changes [61]			Suitable for the disturbances that are not necessary to reschedule	Agent & cognitive technology – cognitive agents HMS & Cognitive factory - Cognitive architecture (beliefs-desires-intentions BDI)
	Reconfigurable manufacturing system (RMS)	1995	Demand for manufacturing responsiveness [60] Limitations from FMS	Designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement/change of its components [53]	• Reduced the set-up / changeover time • Improved flexibility in changing the system itself	Reconfiguration	Does not deal with the entire enterprise, but only with the responsiveness of the manufacturing system	Dedicated transfer lines FMS & CNC machines Reconfigurable machine tools (1970s)

IR	Progress	Emerging time	Challenge faced	Concept implication	Contribution	Major feature	Limitation	Enabling technology/driver
4th IR	Digital and virtual factory	Early 2000s	Product lifecycle management (PLM) software tools/suites still do not fully meet needs and are unaffordable for SMEs [62]	Integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability [28], supporting manufacturing systems design and analysis	• Reduced time and cost in factory planning, design and deployment	Digitalization Visualization Simulation Integration	(Under R&D stage)	CAD/CAM Virtual manufacturing Rapid prototyping ICT – Internet, multimedia, etc. Electronic commerce
	Direct digital manufacturing (DDM)	Late 2000s	**Personalization** Globalization	Took the advantages of both additive manufacturing technology and computer-aided or computer-integrated systems	• Improve the capability of rapid product development • Reduce the lead time or time-to-market • Sustainability	Digitalization Integration	(Under R&D stage)	CAD/CAM; CIM Additive manufacturing technology or RP&M ICT
	Cyber-physical system (CPS)	Late 2000s	**Personalization** Unstable market conditions (uncertainty)	Integrations of computation, networking, and physical processes	• Shorted lead time • Increase variety • Improve quality • Reduce cost • Better services • Sustainability	Integration	(Under R&D stage)	Computer network – Internet of Things Big Data Data acquisition systems Sensor technology Virtual factory or digital factory

3.3 Changes in manufacturing planning tools

Manufacturing planning and control form a major activity component (as management activities) in the process in a manufacturing system (see in e.g. Figure 14). Note that the process in a manufacturing system is not manufacturing process. The former is a set or series of activities taken in order to fill a customer order (as the goal), while the latter refers to subtractive or additive manufacturing process from the machining view.

Manufacturing planning can be aided using software tools since 1960s when modern computers came into application. Progresses in this section can be seen from either a technical or a managerial view.

3.3.1 Single product planning

Single product planning was used in early time when one customer went to craftsmen to order a product for himself/herself. It could also be one project for the purpose of delivering a single product. One classic example of early customization was the Arsenale shipyard in Venice, Italy, one of the largest and most efficient shipyards in the world until the 18th century. Thanks to strong organization of work processes, similar to a modern production line, 16,000 workers were able to build more than 100 ships per year [63].

3.3.2 Bill of materials processor

Owing to the invention of computers/minicomputers along with computing systems in the 1960s, database management systems (DBMS) have been developed for different uses. One of the first DBMSs used for bill of materials (BOM) processing was developed by IBM in the early 1960s.

Bill of Materials gives information about the product structure, i.e., parts and raw material units necessary to manufacture one unit of the product of interest [14]. A computer-based bills of material processor (BOMP) offered the most convenient and efficient method of maintaining up-to-date information about components in the manufacturing industry, according to Nandakumar [64].

A subsequent version of BOMP, Database Organization and Maintenance Program (DBOMP), was a more generalized tool used in manufacturing during the 1970s. IBM softwares, BOMP/DBOMP, were later replaced by VBOMP, vendor of which is H&M Systems Software Inc. in the late 1970s, The new system was claimed to run much faster [65].

3.3.3 Material requirement planning

The concept of material requirements planning (MRP) was first proposed by Joseph Orlicky. Early in its development, MRP was a basic production planning system that required arithmetic. With Gene Thomas, Joseph Orlicky also developed the first piece of MRP software around 1965. With the help of computing power via computers, MRP became faster and more accurate. Later thanks to the popularization of minicomputers, the number of manufacturers utilizing MRP software grew from a handful to nearly a thousand throughout the 1970s [66].

MRP can be regarded as a time phased priority-planning management technique that calculates material requirements and schedules supply to meet demand across all products and parts in one or more plants [14], or a software based production planning and inventory control system used to manage manufacturing processes [24]. MRP is used to expand bills of materials.

MRP systems use four pieces of information as inputs: (1) the master production schedule and (2) the bill of materials determine what materials should be ordered; (1), (2), (3) production cycle times, and (4) supplier lead times, jointly determine when orders for material should be placed. MRP technique focuses on optimizing inventory [14].

3.3.4 Manufacturing resource planning

The next generation or extension of MRP, referred to as manufacturing resource planning (MRP II), incorporates data from beyond manufacturing, including information systems of human resource, finance, accounting, marketing and sales, to create a more holistic system. MRP II is defined as a method for the effective planning of all resources of a manufacturing company [24].

Such an evolution from MRP (which became a part of MRP II) to MRP II, was influenced by trends in business management and facilitated by advances in information technology.

3.3.5 Enterprise resource planning

Enterprise resource planning (ERP) evolved from its predecessors MRP and MRP II in the 1990s and is still popular today. ERP is either defined as an umbrella term for integrated business software systems or viewed as a business approach that starts in the boardroom and permeates the entire organization from a strategic perspective [24].

ERP systems are built on information and integrate processes in an organization using a common database and shared reporting tools [67]. ERP plays an important role in serving as a platform for applications such as customer relationship management (CRM) for supply chain management [68]. They allow software applications that normally do not interact with each other to effectively communicate via integration in a single database.

3.3.6 Strategic enterprise management (SEM)

The development of strategic enterprise management (SEM) system began in the early 2000s. The approach of SEM "seeks to effectively link performance measurement and control to strategic objectives, in an attempt to ensure that operational decision-making is fully focused on delivering strategic objectives" [69].

While some regard SEM systems as a strategic offspring of ERP systems, some argue that SEM systems with a strategic focus are designed to sit on top of the operationally focused ERP systems [70].

3.3.7 Intelligent ERP

The concept of intelligent ERP (or i-ERP) has arisen since 2016. Intelligent ERP systems, incorporating machine learning and advanced analytics, are seen as the next wave of ERP, supporting the digital transformation of companies at the core of their enterprise systems [71].

Intelligent ERP applications, with machine learning and data analytics ability, should be able to forecast, track, learn, route, analyze, predict, report, and manage resources and business processes, and must allow for ongoing reconfiguration to enable process refinements and user experience adaptation [72].

Table 3 – Development in software-based manufacturing planning tools.

Progress	Emerging time	Case	Implication	Major feature	Limitation	Enabling techniques / tools
Bill of materials processer (BOMP)	1960s	BOMP/DBOMP software – IBM; VBOMP – H&M Systems Software Inc.	Simply store bills of material and transaction information	Efficiency	Convenience but with limited functionality	Computers / minicomputers Computing technology
Material requirement planning (MRP)	1965	First MRP software (Joseph Orlicky & Gene Thomas, 1965)	Integrated BOMP with production scheduling and a purchasing plan – Multiple material resource tasks in one suite	Integration within material resources	Difficulty adjusting to changing market conditions, which affected manufacturers ability to plan and adjust	Information technology
Manufacturing resource planning (MRP II)	1980s		Integrated earlier MRP software with financial, personnel, and plant information	Integration in all resources	Could not adjust or integrate supply chain, or present real-time information	
Enterprise resource planning (ERP)	Early 1990s	R/3 software – SAP (1994)	Integrated MRP II software with logistics, supply chain management, human , product lifecycle management, etc. – All facets of the manufacturing business under one solution	Integration in entire business Flexibility [24]	Complex and costly Requires commitment from top-level management and full employees support throughout the organization [67]	
Strategic enterprise management (SEM)	Early 2000s	(Under R&D stage)	ERP systems with a strategic focus	Enterprise integration	(Under R&D stage)	
Intelligent ERP	2016	(Under conceptual stage)	To incorporate ERP application with machine learning and advanced analytics	Intelligence	(Under conceptual stage)	Cognitive technology

3.4 Changes in manufacturing system paradigms (managerial philosophies)

3.4.1 Just-in-time manufacturing

Compared to the software based management techniques – BOMP, MRP, MRP II, and ERP (in Section 3.33.4), just-in-time (JIT) manufacturing also began as a method to reduce inventory levels in Japan. But it later evolved into a management philosophy primarily owing to Taiichi Ohno's contribution work in the development of Toyota Production System (TPS) at the Toyota manufacturing plants around 1950s-1970s. The JIT philosophy is applied in manufacturing that involves having the right items of the right quality and quantity in the right place and at the right time. JIT aims to continuously eliminate waste in all its forms, improve product quality and production efficiency [73].

TPS was officially introduced for publication by Toyota Motor Corporation around 1992. Influenced by the trend in developing autonomous manufacturing, TPS consists of two pillars that are JIT and Jidoka that means "automation with a human touch" or "autonomation", slightly distinguishing itself from JIT and lean manufacturing, TPS does not only eliminate non-value adding activities from processes but also improves the quality of the product with help of Jidoka. [6]. JIT is however more known for the pull system through Kanban control in its contribution to achieving just-in-time manufacturing.

3.4.2 Lean manufacturing

Lean manufacturing or lean production or simply "lean" is also a management philosophy derived mostly from the Toyota Production System, involving a body of knowledge and a comprehensive set of principles and techniques through practices. The definition of lean production in the famous book "The Machine That Changed the World" which made the concept popular in 1990 (although it was first introduced in 1988) is:

- "Use less of everything – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering working hours to develop a new product in half the time. Also, it requires keeping far less than half the inventory on site, results in fewer defects, and produces a greater and ever growing quality of products." [74]

Lean manufacturing is also a manufacturing paradigm of which the core is "elimination of wastes". Through eliminating wastes, lean manufacturing principles guide the way of improving quality and productivity. Lean manufacturing principles also stipulate the adoption of certain techniques, tools, approaches and models in a systematic manner [11]. Most of the techniques/tools/approaches are shared among the similar concepts of TPS, JIT manufacturing, and lean manufacturing. Several of the widely adopted tools are listed in Table 4.

Lean manufacturing is most suitable for applying under standardized working conditions and hence for delivering traditional products and services. A new manufacturing paradigm, agile manufacturing, was raised addressing the challenges caused by dynamically changing customer needs for a variety of products and services.

Early lean manufacturing was achieved in Ford's assembly lines.

3.4.3 Agile manufacturing

When referring to holonic and autonomous manufacturing systems (see in Sections 3.2.7 and 3.2.8), agility is regarded as an objective feature in dealing with changes (or disturbances) of the manufacturing environment. However, agility is much more than that. Agility addresses new ways of running companies to meet challenges of demanding customers seeking high quality and low cost products that are responsive to their specific and rapidly changing needs [13].

Agile manufacturing is a natural development from lean manufacturing in 1990s [13], although the origin of agility as a business concept lies in flexible manufacturing systems [75]. Agile manufacturing is regarded as the combination of flexible manufacturing systems and lean manufacturing paradigm [11]. The paradigm of agile manufacturing was called for and put forward as a manufacturing strategy for the 21st century to meet dynamically changing market requirements and rapidly changing customer demands of goods and services with own specifications. The requirement for organizations and facilities to become more flexible and responsive to customers distinguished the concept of agile manufacturing from lean manufacturing that emphasizes on quality and cost-cutting [13]. Agile manufacturing concepts can be applied both in producing products including offering services.

Agile manufacturing systems should be able to produce efficiently a large variety of products and be reconfigurable to accommodate changes in the product mix and product designs [13]. Reconfigurability and product variety are critical in an agile manufacturing system, functioning as approaches to achieve agility. Comparing with reconfigurability, agility is more as a business philosophy for an entire enterprise. Flexibility and responsiveness are the hallmarks of an agile enterprise [12]. Agile manufacturing requires customer integrated multidisciplinary teams, supply chain partners, flexible manufacturing, computer-integrated information systems, and modular production facilities [76].

Emerging and evolving around the same time as the mass customization paradigm, both were interrelated and focused on challenges from new customer needs for product variety. Some suggested that “agile manufacturing integrates lean principles with mass customization [7]”, while some described that “the output of agile manufacturing paradigm is mass customization [11]”. Overall, mass customization is more like a background paradigm, while agile manufacturing paradigm is more as an approach to address the background challenges.

3.4.4 Supply chain management

Another management approach, similar to PMM, the interest for which has notably increased in the recent decades, is the concept of supply chain management (SCM).

Although first appeared in 1982, the term “supply chain management” was first described by academics from a theoretical standpoint to clarify the difference from more traditional approaches to managing the flow of materials and the associated flow of information until 1990 [77]. Since then, the concept of supply chain management has been broadened and risen to prominence and is still under rising interest at present. Cooper et al. distinguished the concept of SCM from that of logistics management as “an integrative philosophy to manage the total flow of a distribution channel from supplier to the ultimate user” in 1997 [78]. Mentzer et al. defined both a supply chain and supply chain management based on abundant earlier literatures in 2001 [15]. SCM was described as a management philosophy. Chopra & Meidl discussed about supply chain design, planning, and operation and their strategic importance to a firm in their books, the first edition of which was published in 2001 , and the newest sixth edition in 2016 [79].

Trends in global sourcing, an emphasis on time and quality-based competition, and more marketplace uncertainty are some of the drivers for the popularity of the concept [15]. As a consequence of these trends, closer coordination and relationships in a supply chain are necessary. Effective supply chain management involves the management of supply chain assets and product, information, and fund flows to maximize total supply chain surplus [16]. An increase in supply chain surplus increases the size of the total pie, benefiting all contributing members of the supply chain.

The competitive playing field has shifted from company versus company to supply chain versus supply chain. A company's partners in the supply chain may well determine the company's success, as the company is intimately tied to its supply chain [16].

3.4.5 E-manufacturing and E-Commerce

The term of E-Commerce (electronic commerce) is used to describe "any type pf business or commercial transaction involving the transfer of information and/or funds across the Internet" [80]. The adoption of E-commerce began in the late 1990s and has since visibly and significantly impacted the business landscape and led to the emergence of a new type of company – Net enterprises. The manufacturing sector accounts for a relatively large portion of the total e-commerce sales, e.g. around one-sixth in 2004 [80].

3.4.6 Leagile manufacturing

A comparison between lean manufacturing and agile manufacturing is often made. Lean manufacturing shows advantages when applying to high-volume and low-variety production by reducing costs and improving quality, while agile manufacturing is suitable for low-volume and high-variety production in order to meet different customer needs. Leagility combining the advantages of leanness and agility was originally developed to describe manufacturing supply chains in the end of 1990s [81]. Soon after in early 2000s the concept was also applied to a manufacturing system.

3.4.7 Product lifecycle management

Product lifecycle management (PLM) is "the business activity of managing, in the most effective way, a company's products all the way across their lifecycles; from the very first idea for a product all the way through until it is retired and disposed of" [82]. The PLM paradigm is that "a business-oriented, formally-defined, lifecycle, holistic, digital, joined-up and product-focused approach must be taken to the management of a company's products" [82] and emerged in 2001.

PLM is used in both in large multinational corporations and small and medium-sized enterprises (SMEs).

3.5 Changes in other managerial approaches

3.5.1 Taylor's scientific management

Taylor's principles, known as Taylorism or scientific management principles, offered certain solutions to face the challenges emerged due to the 2nd industrial revolution. The mass production was the outcome from applying Taylor's principles. Later in the mid-20th century, the disadvantages of mass production paradigm was pointed out. The paradigm of mass production paradigm led to inefficient usage of resources in the organizations [11] and could not help to address the intense competition any more during the 1970s when Japanese products invaded the global market with better quality and still low price benefiting from their famous Toyota Production System.

3.5.2 Total quality management

When the market competition shifted to quality during the 1970s, the umbrella term of total quality management (TQM) was created for a set of numerous tools, techniques, frameworks, or approaches that were contributed by quality experts. TQM collectively adopted those tools/approaches/etc. and addressed the totality aspect of achieving continuous quality improvement. "Adoption of TQM as a management philosophy for implementing total quality continuously with goal of achieving zero-defect performance and thus facing the onslaught of competition" was the mission in the 20th century [11].

3.5.3 Six sigma

The concept of Six Sigma was first introduced at Motorola by Bill Smith & Mikel J Harry in 1986). Six Sigma is a data-driven quality methodology or approach that can contribute to improved quality and reduce costs by reducing defects and variation in manufacturing and business process control. Six Sigma targets at eliminating defect towards maximum six standard deviations (between the mean and the nearest specification limit) and therefore improving process.

3.5.4 Performance measurement and management

The topic within performance measurement and management (PMM) although emerged since 1980s (focusing on the performance measurement part) and popularized in 1990s, is still a topic of increasing interest and in wide use nowadays. Performance measurement systems (PMS) were defined by Neely et al. in 1995 as "the set of metrics used to quantify both the efficiency and effectiveness of actions" [83]. PMS continue to be critical to the tracking, management and improvement of the competitive performance of manufacturing organizations, owing to constant pressures attributed to technological and competitive changes facing the manufacturing industry [84]. PMM, as the evolution of PMS, contributes to the continuous improvement of performance and so on [83].

3.5.5 Lean six sigma

The concept of lean six sigma that combines lean manufacturing and Six Sigma was first introduced by Barbara Wheat et al. in 2001. Six Sigma does not directly address process speed resulting in the lack of improvement in lead-time in those companies engaged in Six Sigma methods alone. Companies applying lean philosophy alone also showed limitations in improvement due to the absence of a cultural infrastructure [85]. The combination into one methodology could further improve business process, and enhance quality, production and competitive position. The integration is viewed as a new trend in the next manufacturing management wave.

3.5.6 Manufacturing process management

Manufacturing process management (MPM) is a business process that defines how a product is to be produced. MPM receives the definition of a digital product from engineering side, through considering the capabilities and capacities of internal plant and external suppliers, then delivers a set of manufacturing plans required to produce the product. The MPM process can communicate with production planning and control systems (ERP/MES), delivering optimized routings, as well as bills of materials (BOMs) and work instructions, including all supporting documents needed for production operators to manufacture the product [86]. To improve the MPM process is essential to address challenges in cost, time, and quality.

3.5.7 Product variety management

As the number of product variants has increased sharply in the recent decades under the manufacturing paradigm of customization, a great challenging in the manufacturing industry is to manage variety through the entire product lifecycle. The right range of variants is an important issue since more product variants incurs more expenses although they are able to meet more customer needs. Product variety if well-managed can offer the potential to expand markets, increase sales volume and revenues [87]. This leads to the emergence of product variety management.

Several of the above managerial approaches are under discussion for their application in SMEs, as listed in Table 5.

Table 4 – Development in manufacturing management methods.

Progress	Emerging time	Challenge faced	Implication	Major feature	Limitation	Enabling techniques / tools
Taylorism and scientific management	1909	Large demands for goods and services	Lead to mass production and division of labor	Efficiency	Inefficient usage of resources in the organizations [11] The division of labor caused problems between management and workers	---
Just-in-time (JIT) manufacturing	1960s-1970s	In response to changing customer demands	Keep material/product, people, production equipment, workspace, etc. responsive to what/when/where/how much are needed by reducing waste	Responsiveness	*Some limitations of JIT see in [73]	Kanban 5S/6S Value stream mapping Single-Minute Exchange of Die Etc.
Total quality management (TQM)	1970s	Market competition on quality	Achieve continuous quality improvement	Quality	Difficult, comprehensive, and long-term process	
Lean manufacturing	Early 20th century	Mass production	*The roots of lean manufacturing [11] Reduced inventory and minimized the material handling distance and ptoduction cost though continuous flow	Lean	The same product to any customer – no flexibility	
	1970s	Market competition on cost and quality	Reduced cost and improved quality and efficiency by eliminating waste (Muda) and continuous improvement (Kaizen)		Most suitable for standardized working conditions and hence traditional products and services	
	1990		*Popularized the concept of lean production		The discipline required to implement lean is often counter-cultural; adaptation is often constrained	
Performance measures and management (PMM)	1980s (still popular)	Market competition on quality	Tracking, management and continuous improvement of the competitive performance of manufacturing organizations	Performance	Limitations from quantitative methods Long-term process	Computing power
Six Sigma	1986	Market competition on quality	Improved quality and reduced costs by reducing defects and variation in manufacturing and business process control	Quality	Six Sigma alone does not directly address process speed resulting in the lack of improvement in lead-time	Control chart; Pareto chart; root cause analysis; SIPOC analysis; etc.
Agile manufacturing	1990s	Mass customization Rapidly changing consumer need for low-cost, low-volume and high-variety products	Capable of producing efficiently a large variety of products and being reconfigurable to accommodate changes in the product mix and product designs Integration of lean principles with mass customization [12] through reconfiguration	Agility	Agile manufacturing requires customer integrated multidisciplinary teams, supply chain partners, flexible manufacturing, computer-integrated information systems, and modular production facilities	CAD/CAM, CNC, RP&M, mobile robots, intelligent pallets, AGV system, flexible fixtures, and flexible manufacturing cells Internet, WWW, EDI, Multimedia, and E-Commerce [13]

Progress	Emerging time	Challenge faced	Implication	Major feature	Limitation	Enabling techniques / tools
Supply chain management (SCM)	1990s (still popular)	Globalization Trade liberalization	Involveing the management of supply chain assets and product, information, and fund flows to maximize total supply chain surplus	Integration	Uncertainty	---
E-commerce	Late 1990s	Globalization Trade liberalization	Impacted the business landscape and led to the evolution of Net enterprises [80]	Virtualization	Network security	ICT - Internet; WWW
Leagile manufacturing	Around 2000	Limitations from both lean and agile manufacturing	*Combined lean manufacturing and agile manufacturing	Leagility	Could be difficult to implement or achieve	*See in “Lean manufacturing” and “Agile manufacturing”
Lean six sigma	2001	Limitations in improvement when only one is applied	*Combined lean manufacturing and Six Sigma	Quality Efficiency	Management knowledge skills required	*See in “Lean manufacturing” and “Six Sigma”
Product lifecycle management (PLM)	2001	Sustainability	PLM manages, in an integrated way, all of its parts and products, and the product portfolio, not just managing one of its products. “Managing products across their lifecycles”	Integration	PLM software tools/suites still do not fully meet needs and are unaffordable for SMEs [62]	---
Manufacturing process management (MPM)	2000s	Market competition on lead-time	Accelerate the process design and planning	Digitalization	Application suites are unaffordable for SMEs	ERP, MES, BOMs
Product variety management (PVM)	2010s	Mass customization and personalization	Product variety if well-managed can offer the potential to expand markets, increase sales volume and revenues [87]	Variety	More product variants incurs more expenses. The right range of variants is an important issue.	FMS, RMS, Agile MS Group technology

3.6 Summary

It is important to review the traditional manufacturing systems in order to understand the differences between common approaches and to comprehend the emergence of new types of manufacturing systems, concerning why a new type of manufacturing system is needed and how it should be designed and developed. A historical perspective better helps us to gain an insight into the backbone cause and effect.

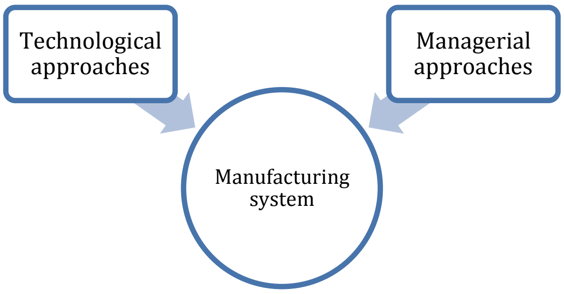

Figure 16 – A simple structure reflecting the structure in this work.

In Chapter 2, a literature review on the concept of manufacturing system is conducted from different aspects (e.g. definition, components, levels, and some functional types). In this chapter, a comprehensive literature review on the development of manufacturing systems is conducted from historical perspectives. The development of manufacturing systems mainly comes from two directions as shown in Figure 16 (under each two/three sub-categories are discussed):

- technological approaches:
    - changes in machining/manufacturing process methods;
    - changes in manufacturing system paradigms from the technological view;
- managerial approaches:
    - changes in manufacturing planning tools;
    - changes in manufacturing system paradigms from the managerial view (including manufacturing paradigms or management philosophies);
    - changes in other managerial approaches (including management techniques or principles)

Back to Chapter 1, we have discussed the evolution of the manufacturing industry also from a historical perspective, i.e. the background of the development of manufacturing systems, including the evolution of industrial revolutions, the shifting of manufacturing paradigms, and the changes in the focuses of customer demands and market conditions.

The future of manufacturing systems is exciting. With the development of mobile technology, cloud computing, Internet of Things, and Big Data, etc., manufacturers are able to response with more agility than ever before to rapidly changing customer needs with own specifications and dynamically changing market conditions, based on more accurate information. Holon technology allows manufacturing systems to react to changes in the system environment in real-time. Under the influence of Industry 4.0, the new manufacturing paradigm of personalized production with small or one batch size, globalization of market and challenges specially faced by SMEs, a new type of manufacturing system is put forward, named "**Small-scale Intelligent Manufacturing System**" (SIMS).

As a summary of discussions from Chapter 1, 2, and 3, a historical overview regarding progresses and trends in the evolution of the manufacturing industry and in the development of manufacturing systems, connected though a timeline, is presented in Table 5.

Table 5 – A historical overview on the progresses and trends in the manufacturing industry and manufacturing systems.

Time	Before 1760s	1760s to 1840s	1860s to 1910s	Late 1960s – 1980s	During 1990s	From late 1990s – 2010s
Emerging paradigm	***Progresses in the evolution of manufacturing industry***					***Trends in manufacturing industry***
Customer needs & expectations	Customers request products	Customers buy whatever available in the market and prefers as cheap as possible		Customers buy whatever they wishes to buy through selecting among alternative products [20]	Manufacturers designed the basic product architecture and options while customers are allowed to select the assembly combination that they prefer most [9]	Customer orders products satisfying their specific needs; individual customers can be provided with unique products
Market competition focus (Market winner)	Cost (although low market competition)			Quality (1970s) Cost (late 1980s) [75]	Variety (or availability [75])	Lead time [75] Service level
Industrial revolution (IR)	Earlier IR	1^{st} IR (1784)	2^{nd} IR	3^{rd} IR		4^{th} IR (2010s)
Manufacturing paradigm	Craft production [9]		Mass production		Mass customization	Personalization
Emerging technology	***Progresses in the development of manufacturing systems (technological approach)***					***Trends in manufacturing systems***
Manufacturing system paradigm (technological approach)	Manual tools	Semi-automatic machines & factory system	Assembly lines & automatic machines	Automated MS (1960s) FMS & CIM (1970s)	HMS & Autonomous MS; RMS (1990s)	Digital and Virtual factory Direct digital manufacturing Cyber-physical system (CPS) Unmanned factory / Factory of the Future
	Earlier tools / machines			**Traditional manufacturing system**	**Intelligent manufacturing system (IMS)**	**Small-scale Intelligent manufacturing system (SIMS)**
Manufacturing / production method	One piece manufacturing (single product/project/one-off)		Flow manufacturing (continuous/repetitive)		Intermittent manufacturing (batch/job shop)	One piece manufacturing (single product/project/one-off)
Machining / manufacturing processing method	Removal machining / subtractive manufacturing (manual or semi-automatical)			Subtractive manufacturing (CNC machining)	Additive manufacturing (3D printing, etc.)	Hybrid manufacturing (2010s)
Production power / energy	Hand power & animal power	Water and steam power	Electrical power		Renewable energy (e.g. wind power)	Sustainable energy (e.g. bioenergy)
Transportation mode	Packhorses River navigations	Contour canals Railroads	Road vehicles Maritime	Air	Intermodal	Next-generation (NextGen) aircrafts & vehicles (gas-electric hybrid buses)

Time	Before 1760s	1760s to 1840s	1860s to 1910s	Late 1960s – 1980s	During 1990s	From late 1990s – 2010s
Emerging method	***Progresses in the development of manufacturing management methods***				***Trends in manufacturing management methods***	
Manufacturing management method	Simple management		Early lean manufacturing (Ford, 1870) Scientific management (Taylor, 1909)	JIT manufacturing (1960s/70s) Total quality management (1970s) Management by objectives (1980s) Lean manufacturing (1970s-1990) Six Sigma (1986)	Performance measurement & management (PMM) (1980s/90s) Agile manufacturing (late 1990s) Supply Chain Management (1990s) E-Commerce (late 1990s)	JIT in SMEs [88] Leagile manufacturing (2000s) [89] Lean Six Sigma (2001) Product lifecycle management (2001) Manufacturing process management [86] PMM in SMEs [83] Lean in SMEs [90] Product variety management [87]
Manufacturing planning and control method	Single product planning		Bill of material (manual)	BOMP (1960s) MRP (1960s/70s) MRP II (1980s)	ERP (1990s)	Strategic enterprise management (early 2000s) i-ERP (2016)
Shifting focus	***Changes in the focus of manufacturing-related approaches***					
Manufacturing / production method	One piece manufacturing (single product/project/one-off)		Flow manufacturing (continuous/repetitive)		Intermittent manufacturing (batch/job shop)	One piece manufacturing (single product/project/one-off)
Production volume-product variety relation	Low-volume & low/high-variety		High-volume & low-variety		Medium-volume & high-variety	Low-volume & high-variety (unique)
Manufacturing interaction strategy	Make to order		Make to stock	Assemble to stock	Make to order	Engineer to order
Manufacturing layout design	Fixed position layout (project layout)		Product layout (flow shop)	Automated production line (transfer machine)	Functional layout (process layout / job shop) Cellular layout	Digital factory/Virtual factory
Manufacturing layout management	Workshop management		Factory shop management		Functional management	Process management
Human's role	Hand craft in workshop		Labor-intense in factory shop	Automated manufacturing systems replaced part of labors	Artificial intelligence replaces part of human work	Unmanned factory (Autonomous) (Remote) monitor, control, and management Increasing collaboration among partners

4 Developing Small-scale Intelligent Manufacturing Systems (SIMS)

4.1 Background of developing SIMS

In Chapter 1, we have discussed that manufacturers face challenges mainly from two directions: customers and market; and new Industrial Revolution or manufacturing paradigm. Challenges for manufacturers in the northern peripheral and arctic (NPA) region (mostly SMEs) have also been discussed. These challenges have together led to the emerging concept and initiative of small-scale intelligent manufacturing systems (SIMS), targeting at enhancing the competitiveness of SMEs in the NPA region though meeting new customer demands and adapting to the new Industrial Revolution – Industry 4.0 and the new manufacturing paradigm – Personalized production.

In a summary, the three major factors that lead to the emerging of the SIMS initiative are:

1) *(From the viewpoint of customer)*: rapidly changing customer needs and globalization of markets and enterprises;
2) *(From the viewpoint of industry)*: shifting manufacturing paradigms and the coming era of Industry 4.0;
3) *(From the viewpoint of enterprise)*: challenges faced by SMEs in the resourceful NPA region.

Regarding these background facts, relevant contexts are described in detail in the following sections and can also be found in Chapter 1 (from historical perspectives).

4.1.1 Manufacturing paradigm shift

Customer needs and market competition have increased sharply since more than one century ago and customer choices have also enlarged sharply in the recent decades. Driven by changing demands from human beings and supported by constantly advancing technologies, the manufacturing paradigm has shifted from the very early craft production to mass production along with the arising of the 2nd Industrial Revolution to mass customization from the late 1980s. Extending from mass customization, personalization has already appeared to be within reach since the late 1990s. Building a unique product for each customer has been a popular trend lately.

Craft production offers high flexibility for customers but comes with a high cost. The focus of **mass production** is efficiency through stability and control and the goal is to develop, produce, market, and deliver goods and services which are often standardized at prices low enough that nearly everyone can afford them [91]. **Mass customization**, different from mass production, seeks as its goal to develop, produce, market, and deliver affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want, and focuses on variety and customization through flexibility and quick responsiveness [91]. Mass customization was also described as "low-cost production of high variety, even individually customized goods and services" by B. Joseph Pine II in 1993 [92].

The trendy paradigm of **personalization** or **personalized production** [9], developed from individualized customization, can be seen as the next wave from mass customization. Compared to mass customization in which customers can only select a preferable assembly combination based on basic product architectures, customers can now influence or participate in the design of products and even in simulation, prototyping and manufacturing processes. Personalization aims to tailor-made goods and services to the preferences of individual customers. A unique product can be provided for each single consumer.

To better distinguish the four manufacturing paradigms, here we differentiate them by the scale of production volume and product variety:

- ***Craft production***: low-volume production, low/high-variety product (depending on craft skills);
- ***Mass production***: high-volume production, low-variety product;
- ***Mass customization***: medium-volume production, high-variety product;
- ***Personalized production***: low-volume production, high-variety product.

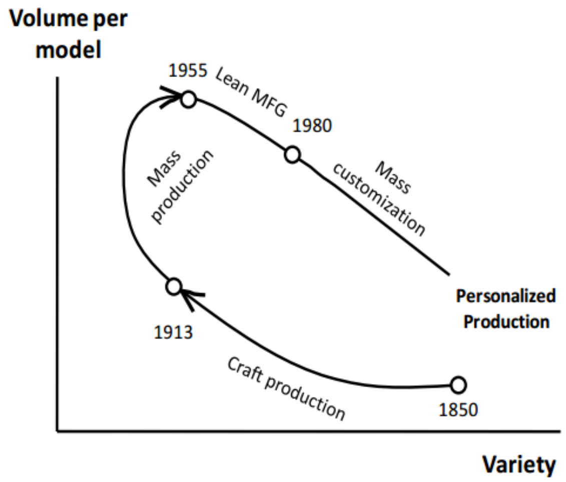

Figure 17 – Linking manufacturing paradigms with production volume and product variety [9].

Figure 17 reveals the evolution of the volume-variety relationships in different manufacturing paradigms. The manufacturing paradigm shifts result in shortening product development cycles and shortening product life cycles.

While mass production and mass customization provide products through large-scale manufacturing, personalized production can be achieved through small-scale manufacturing. This necessitates the development of the SIMS concept. Existing theories and practices in manufacturing are mostly directing large-scale manufacturing in large-sized companies. Problems might arise when they are applied to small-scale manufacturing and SMEs. The initiative of SIMS aims to look into and solve potential problems that will occur in transforming ways of manufacturing and business processes while adapting to the emerging manufacturing paradigm of personalization and the new era of Industry 4.0.

4.1.2 Industry 4.0

Customer-driven manufacturing paradigm shifts and technology-driven industrial revolutions at four different periods have been introduced in Chapter 1 from historical perspectives. Industrial revolutions act as the major background change or challenge (from the industrial perspective) that leads to more changes in the development of manufacturing systems from different aspects.

Figure 18 summarizes the four stages of the industrial revolutions:

1) the mechanization of manufacturing facilities powered by water and steam in Industry 1.0;
2) the introduction of assembly lines for mass production powered by electricity in Industry 2.0;
3) the automation of manufacturing processes using electronic and IT systems in Industry 3.0; and

4) the autonomation of manufacturing using cyber-physical systems and the digitalization and integration of value networks utilizing Internet of Things in Industry 4.0.

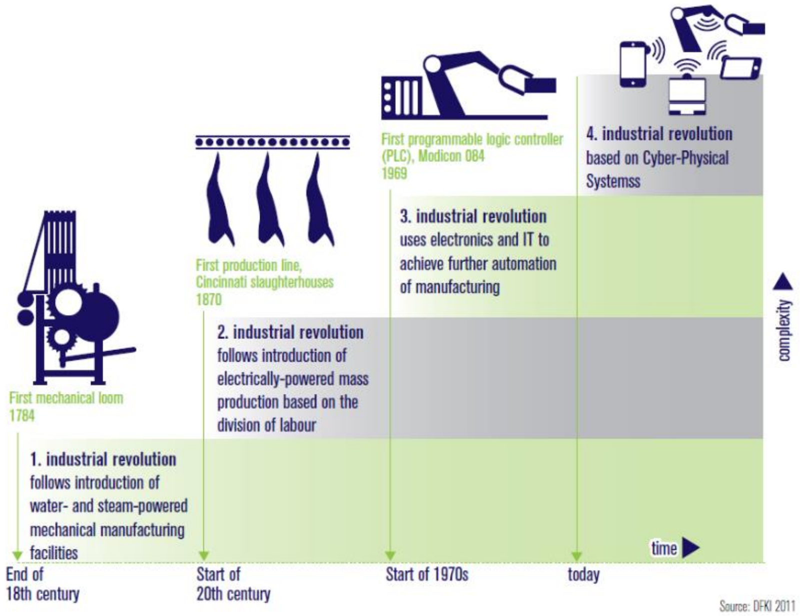

Figure 18 – The four stages of the industrial revolution [93].

The concept of Industry 4.0 (or “Industrie 4.0”) originated in Germany at the beginning of 2010s, and stands for the 4th industrial revolution. Here, Industry 1.0, 2.0, and 3.0 stand for the 1st, 2nd, and 3rd industrial revolutions, respectively. There are many definitions for Industry 4.0, explaining it from different point of views, e.g.:

- *Industry 4.0 is “a comprehensive transformation of the whole sphere of industrial production through the merging of digital technology and the Internet with conventional industry”* [1]. *(by the German Federal Government/ Federal Chancellor Angela Merkel)*
- *“Industry 4.0 is a vision of integrated industry implemented by leveraging cyber-physical systems, embedded computing, and Internet of Things technologies”* [8].
- *“Industry 4.0 is a holistic automation, business information, and manufacturing execution architecture to improve industry with the integration of all aspects of production and commerce across company boundaries for greater efficiency”* [8].
- *“Industry 4.0 is a term applied to a group of rapid transformations in the design, manufacture, operation and service of manufacturing systems and products”* [94].

In the manufacturing environment of the new stage, vertical networking, end-to-end engineering and horizontal integration across the entire value network of increasingly smart products and systems is set to usher in Industry 4.0 [93]. The entire value chain is organized and managed over the life cycle of products that is based on increasingly personalized customer requirements and extends from the product idea, test and development to its manufacturing and delivery to the end customer and ultimately to its recycling, including all associated services.

4.1.3 Small and medium-sized enterprises

Small and medium-sized enterprises (SMEs) play a key role in driving economic growth and job creation and ensuring social stability worldwide, despite that different definitions of SMEs (often with large distinctions) are applied in individual countries [95, p. 9].

SMEs including micro enterprises in the European nations are currently defined as enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million [96]. Table 1 shows the criteria for medium, small and micro-sized enterprises, respectively.

Table 6 – Criteria for medium, small and micro-sized enterprises in the EU [97].

ENTERPRISE CATEGORY	*PERSONS EMPLOYED*	*TURNOVER OR*	*BALANCE SHEET TOTAL*
MEDIUM	< 250	≤ € 50 m	≤ € 43 m
SMALL	< 50	≤ € 10 m	≤ € 10 m
MICRO	< 10	≤ € 2 m	≤ € 2 m

According to the official statistics [97], SMEs represent over 99% of all enterprises, account for around two-thirds of total employment, and contribute near 60% of gross value added in the European Union (EU) and also in Norway. SMEs also stimulate entrepreneurial spirit and innovation and are thus crucial for fostering competitiveness and employment [96].

Under the influence of global economy, internationalisation is important for the competitiveness of enterprises of all sizes, no exception (or particularly) for SMEs [95]. SMEs are a major focus of EU policy, given their importance to Europe’s economy [96]. Public policy at local, regional and national level plays a significant role in encouraging internationalisation of SMEs and assisting them to realise their full potential in global markets.

The industrial/manufacturing sector is one of the major sectors for both large companies and SMEs. The small and medium-sized manufacturing enterprises are now facing new challenges when embracing the upcoming era of Industry 4.0. For example, SMEs require flexible organisational structures because business areas that at present are clearly separated from one another are increasingly becoming interconnected, in order to substantial achieve advances in productivity raised by technological developments [98]. Note that the term “SMEs” used in the following parts of this work usually refers to small and medium-sized manufacturing enterprises/firms/companies.

4.2 Purpose of developing SIMS

While the small and medium-sized manufacturers, especially in the remote NPA region, are facing intense competition and considerable challenges, external organizations (e.g. research institutes, government organizations) are actively seeking new approaches and measures to support SMEs against competition and challenges, leading to the emerging of the SIMS initiative. The ultimate goal of developing SIMS is to enhance the competitiveness of SMEs. Corresponding to the three background facts mentioned in Section 4.1, the SIMS initiative is aiming to realize the following sub-goals:

1) *(From the customer level or product/production level)*: Quick changeover of manufacturing systems to meet customer demands and new markets;
2) *(From the industry level)*: Transformation of SMEs to adapt themselves from the era of Industry 3.0 to Industry 4.0;
3) *(From the enterprise level)*: Overcoming challenges caused by the enterprise size and location.

In order to achieve the above goals, the primary approach is to integrating technological, business, marketing and organizational transformation to strengthen the overall competence of SMEs where innovation is imperative. There are four types of innovation (the "4Ps" of innovation) [17]:

- ***Product innovation***: changes in the products/services;
- ***Process innovation***: changes in the ways in which they are created and delivered;
- ***Position innovation***: changes in the context in which the products/services are introduced;
- ***Paradigm innovation***: changes in the underlying mental models which frame what the organization does.

While the small scale of SMEs has always been a major restriction on further development of enterprises, new manufacturing paradigms and new technologies make SMEs rethink their roles and positions in the new era. Not only do SMEs want to break through the limitations caused by the small size (and distant location), they also want to benefit from this unique characteristic, distinguishing themselves from those large companies. It could be not easy but somewhere possible. Such a thinking also makes up a start point for initiating SIMS.

4.3 Benefit of developing SIMS

The development of SIMS is supposed to bring significant benefits for different partners (e.g. industries, manufacturers, and customers), presented in Table 7.

Table 7 – Benefits to be brought by SIMS for different partners from several criteria.

Targets / Criteria	**Industries**	**Manufacturers**	**Customers**
Production- / product-related	Manufacturing paradigm shift: towards personalization	Highly flexible personalized production that can be rapidly reconfigured to changing demands, yet still at low cost and high quality	Personalized products that meet customer needs at relatively affordable prices
Environment to the above	Towards Industry 4.0	A highly integrated, digitalized, automated and autonomous, and efficient manufacturing environment	E-commerce Virtual engineering
Supply chain-related	Cooperative supply chains under unstable market conditions from globalization	A connected and responsive logistics network for SMEs	Promptness of delivery
Customer-related	Customer-oriented product life cycles	Customer-to-business (C2B) connected agile enterprise	Better services (e.g. quick response and specific customer experience)
Sustainability-related	Sustainable development in the industry (social, economic, & environmental)	Sustainable production (e.g. user/resource/energy/ environment-friendly)	Sustainable products (reduce, reuse, & recycle)

Table 7 shows a summary and mix of what have been discussed and achieved from the existing manufacturing methods and those still in trend for the future manufacturing.

From Table 7, we can notice that the future manufacturing will focus more on the needs of human beings where customers are a central part, and workers/employees in the manufacturing enterprises are also included. For example, a customer-oriented product life cycle means that customer wishes are adopted in all life-cycle phases from the initial product idea, development, production, use and maintenance to recycling and all associated services in order to make improvements continually and responsively. Cost, quality, and responsiveness, are still the major factors that need to be taken into consideration as primary objectives in developing SIMS, while variety and service are the rising factors from the paradigms of customization and personalization. Sustainability is also a rising factor to be considered as an objective. Flexibility & agility, automation & autonomation, digitalization, integration and connectivity are some of the crucial features for SIMS. These objectives and feature will be further discussed in Chapter 6.

Figure 19 summarizes the background and purposes/goals of developing SIMS and one general approach to achieve the goals. With the benefits of developing SIMS, the incentives for developing SIMS have been discussed.

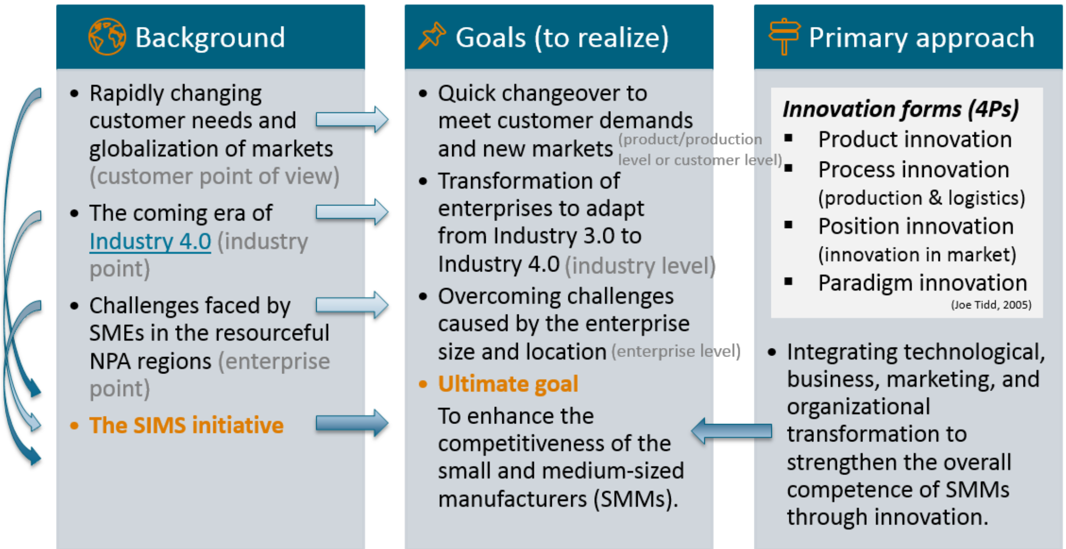

Figure 19 – A mapping relating the background and goals of developing SIMS.

4.4 Necessity of developing SIMS from supply chain perspective

The globalization and trade liberalization from the end of the 20th century have formulated unstable market conditions (more uncertainty in the market place) and intensified market competition in the business environment [14]. International cooperation and technological innovations further increased competition. Meanwhile, customer needs are becoming more and more demanding regarding price/cost, quality, variety/selection, lead time/promptness of delivery, and service.

Changing customer demands, trends in global sourcing, and more international cooperation among enterprises have all put manufacturers including SMEs into closer relationships within supply chains or value networks. The competitive playing field has shifted from enterprise versus enterprise to supply chain versus supply chain. A manufacturer’s partners in the supply chain may well determine the manufacturer’s success, as it is intimately tied to its supply chain [16].

Under such a background, manufacturing systems should adapt themselves into the supply chain perspective. Supply chain integration and relevant management should be focused on.

5 An architecture for manufacturing system from supply chain perspective

Due to several factors such as changes in market conditions and customer expectations and requirements, progresses in technology and managerial methods, the nature, objectives and features of manufacturing systems have been frequently changing accordingly.

Although manufacturing systems have been widely discussed regarding all aspects from definition, components, types, to applicable technologies or managerial methods, etc., there has not yet been found an architecture for defining a complete manufacturing system. In the previous chapter (in Section 4.4), the necessity of developing a new manufacturing system from the supply chain view has been discussed. Based on the concept of supply chain management including three types of actors (suppliers, manufacturers, and customers) and three types flows (product, information, and fund flows) and other existing understanding from literatures (see in Chapter 2), a systematic architecture for an integrated manufacturing system (relatively complete) is developed in this chapter, as shown in Table 8.

The built architecture for manufacturing system (MS) mainly consists of three parts under which there are related elements:

1) ***Basic components***: human actors; funds; information; physical systems; and decision systems.
2) ***Sub-components*** corresponding to each basic component:
   A) ***Human actors***:
      i) Suppliers (external actors);
      ii) Employees in the manufacturing enterprise (internal actors);
      iii) Customers (external actors).
   B) ***Funds***: funds in the form of capital or cash and fund flow between customers and manufacturer, manufacturer and suppliers.
   C) ***Information***: information and information flow between customers and manufacturer, manufacturer and suppliers. (Note that how the information flow or fund flow is generated and in which ways the flows are realized are parts of the decision or physical systems.)
   D) ***Physical systems***, including materials/products (i, ii, & iii) which make up material/product flow, and facilities/equipment/etc. (iv) which function as, for example, logistics carrier, production transformer, or office configuration (hardware, software, or other tools):
      i) Raw materials or original components purchased from suppliers;
      ii) Work-in-process components or semi-finished products; generated wastes;
      iii) Finished products to be sold or distributed to customers;
      iv) Facilities; machines/equipment; operating environment; energy; etc.
   E) ***Decision systems*** *(or decision structures)* for operating MS, including business activities (i & v) and logistics activities (ii, iv, & vi) supporting material flow, production processes to transform inputs to outputs (iii), and supporting management activities (vii):
      i) Procurement from suppliers (or supply from the view of suppliers);
      ii) Delivery from suppliers to manufacturer;
      iii) ***Process for manufacturing***;
         (a) Design & prototyping;
         (b) Process planning;
         (c) Production planning and control;

(d) ***Manufacturing***: transforming inputs into respective products through processes (as designed in accordance with the process and production plans) [35];
(e) Assembly & Packaging;
(f) Quality control;
(g) Warehousing.

iv) Internal transportation/logistics in the manufacturing plant;
v) Sales and marketing to customers (or order/demand from the view of customers);
vi) Distribution from manufacturer to customers;
vii) Management (as activity).

3) ***Associated knowledge and skills*** from internal human actors:
A) Managerial methods and skills;
B) Knowledge in technology and technical skills.

Table 8 – An architecture for manufacturing system from the supply chain stage perspective.

<table>
<tr><td rowspan="14">MANUFACTURING SYSTEM</td><td>Basic components</td><td colspan="4">Corresponding sub-components from three sides</td><td colspan="2">Knowledge & Skills</td></tr>
<tr><td>Human actors</td><td>(Suppliers)</td><td>Employees in the manufacturer</td><td>(Customers)</td><td rowspan="13">Management</td><td rowspan="13">Managerial skills</td><td rowspan="13">Technology & Technical skills</td></tr>
<tr><td>Funds</td><td colspan="3">Funds (flow)</td></tr>
<tr><td>Information</td><td colspan="3">Information flow</td></tr>
<tr><td rowspan="2">Physical systems</td><td>Raw materials; Components</td><td>Components; Semi-finished products; Wastes</td><td>Finished products</td></tr>
<tr><td colspan="3">Facilities; Machines; etc.</td></tr>
<tr><td rowspan="8">Decision systems</td><td>Delivery</td><td>Transportation (Internal logistics)</td><td>Distribution</td></tr>
<tr><td rowspan="7">Procurement (Supply)</td><td>Design & Prototyping</td><td rowspan="7">Sales & Marketing (Order/Demand)</td></tr>
<tr><td>Process planning</td></tr>
<tr><td>Production planning and control</td></tr>
<tr><td>Manufacturing</td></tr>
<tr><td>Assembly & Packaging</td></tr>
<tr><td>Quality control</td></tr>
<tr><td>Warehousing</td></tr>
</table>

The above architecture for manufacturing system (MS) in Table 8 gives a general idea of what make up a MS, covering the major aspects in a MS including:

- human actors and their associated knowledge or skills (in purple);
- their activities in operating the MS (in orange);
- the accompanying three types of flow (material/product, fund, and information flow) from related activities in the supply chain (in green); and
- physical carriers.

These aspects are illustrated in Figure 20, which can be seen as another form of Table 8, both aiming to define a manufacturing system. While Table 8 emphasizes on relating physical and decision systems to three different stage/actor sides – supplier, manufacturer, and customers – from the stage view, Figure 20 presents a summary of different types of human actors, activities, and flows.

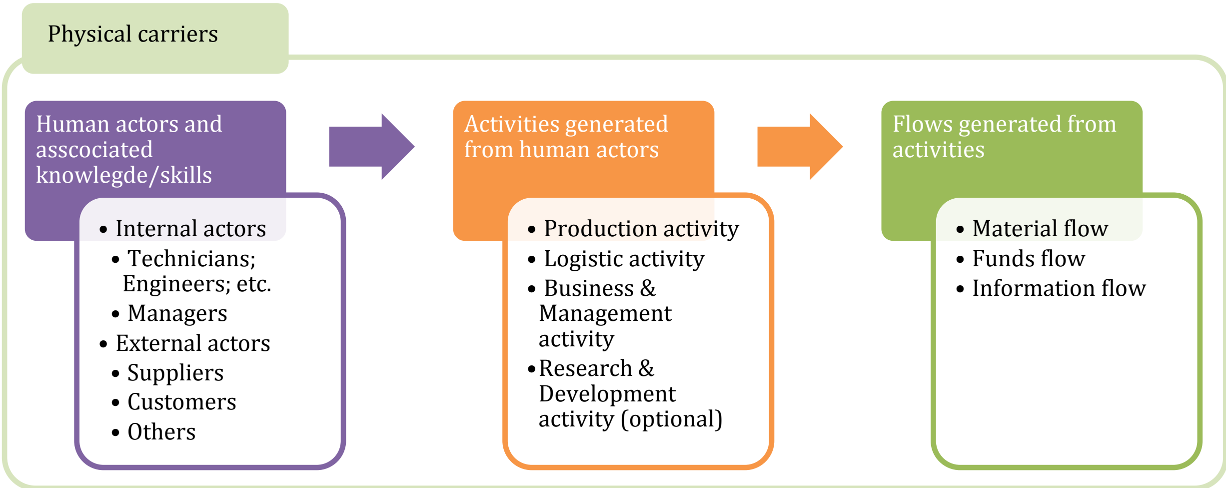

Figure 20 – A structure for manufacturing system from the supply chain logical view.

5.1 Manufacturing system management

Management activities in a manufacturing system are detailed in Table 9, corresponding to basic components and their sub-components. The developed architecture for manufacturing system in Table 9 is closely related to the concept of supply chain. A supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request [16]. The stages in a supply chain includes not only the manufacturer, suppliers, and customers, but also transporters, warehouses, retailers, or wholesalers/distributors. Two major stages as external actors – **suppliers and customers – are included** in the manufacturing system in Table 9. This forms one new feature comparing to the traditional definition of manufacturing systems that only include internal actors like employees or labour forces.

A manufacturer's partners in the supply chain may well determine the manufacturer's success, as it is intimately tied to its supply chain [16]. In this sense, management in a MS might be considered as in the form of supply chain management. All supply chain processes in a firm can also be classified into the following three macro processes [16]:

- **Supplier Relationship Management** (SRM): processes that focus on the interface between the firm and its suppliers;
- Internal Supply Chain Management (ISCM): processes that are internal to the firm;
- **Customer Relationship Management** (CRM): processes that focus on the interface between the firm and its customers.

Regarding internal human actors, the relevant management activity is **human resource management**. A supply chain is dynamic and involves the constant flow of information, product, and funds between different stages [16]. Each stage in a supply chain is connected through the flow of products, information, and funds. For a traditional manufacturing system in which suppliers and customers are regarded as external actors, there are still (internal) information flow and (internal) product/material flow within the manufacturing enterprise. Funds do not generate flow but exist in some capital form.

Table 9 – An architecture for manufacturing system with specified management activities.

MANUFACTURING SYSTEM	Basic components	Corresponding sub-components from three sides			Management activities
	Human actors	Suppliers	Manufacturer	Customers	Supplier/customer relationship mng.
		Employees in the firm			Human resource management
	Funds	Funds (flow)			Financial management
	Information	Information flow			Information management
	Physical systems	Raw materials; Components	Components; Semi-finished products; Wastes	Finished products	Materials management
		Facilities; Equipment; Environment; Energy; etc.			
	Decision systems	Delivery	Transportation (Internal logistics)	Distribution	Logistics management
		Procurement (Supply)	Design & Prototyping	Sales & Marketing (Demand)	Product management
			Process planning		Demand & Order management
			Production planning and control		Manufacturing planning and control
			Manufacturing		Capacity management
			Assembly & Packaging		
			Quality control		Quality management
			Warehousing		Inventory & Warehouse management

The design and management of these flows are closely connected to the success of the supply chain and hence the success of the manufacturing enterprises. **Materials management** is responsible for the flow of materials [99], and management for the flows of information and funds are named as **information management** and **financial management**, respectively, for the purpose of this work.

Based on [99], materials management could cover the following aspects:

- Product & process management – product design and development; process design and improvement;
- Demand management
    - Demand forecasting;
    - Order processing (order from customers);
    - Making delivery promises (delivery to customers);
    - Interfacing between manufacturing planning and control and the marketplace.
- Manufacturing planning and control (in five hierarchical level);
    - Strategic business plan;
    - Production plan (sales and operations plan);

    - Master production schedule;
    - Material requirement plan;
    - Purchasing and production activity control.
- Capacity management;
- Inventory management (inventory planning, record, and control);
- Order management (order to suppliers for purchasing);
- Quality management (quality planning, assurance, and control);
- Warehouse management;
- Logistic management (transportation and distribution).

5.2 Manufacturing system components in different levels

In order to make better understanding on relationships among components, activities or functions, manufacturing systems are often divided into several levels (see in Section 2.7).

When dividing manufacturing system into hierarchical levels, we first separate the decision (or decision-making) systems from the physical systems. A five-level hierarchy (a new level added to [29]) is adopted here for the physical systems in a typical manufacturing system:

- ***Value chain/network***: a system that is part of a value network;
- ***Enterprise/firm level***: a system that has its own independent management;
- ***Shop floor level***: a sub-system of an enterprise where manufacturing activities are carried out;
- ***Cell/line level***: a group of machines that produce a part;
- ***Machine level***: a single entity that changes the input material.

The decision systems in a manufacturing system are commonly decomposed into three levels with different time frames (or horizons or scales).

- ***Strategy decision level***: long term decisions;
- ***Tactical decision level***: medium term decisions;
- ***Operational decision level***: short term scheduling.

A major application of this three-level method is in the decision categories or phases of supply chain management. Successful supply chain management requires many decisions relating to the flow of information, product, and funds. These decisions fall into three categories, depending on the frequency of each decision and the time frame during which a decision phase has an impact:

- supply chain decision design or strategy;
- supply chain decision planning;
- supply chain decision operation.

Detailed descriptions of the three categories of decisions can be found in [16]. Each decision phase must consider uncertainty over the decision horizon.

The five hierarchical categories of manufacturing planning and control (system) have been mentioned in Section 5.1. Corresponding capacity or resource planning activities to each category can be found in [99] and both are listed in Table 10. Decision phases in supply chain management and categories of manufacturing planning and control and its application tools can be linked through time scales.

Table 10 summarizes several major manufacturing system components under three major categories of operational, tactical, and strategic levels. These three categories can be applied to both the decision systems and the physical systems. The two types of systems can be linked through the material/product type to which manufacturing planning and control activities can apply.

With the rising applications of sensor technology and the trend in achieving accurate real-time information and referring to Rogers's seven-level manufacturing decision hierarchy (in Figure 11), a new (and rough) hierarchical framework of manufacturing system components in different levels based on Table 10 is suggested, as presented in Table 11.

The new framework with four main levels (in Table 11 with one column added in darker color) is heuristic and benefits from the interrelationships among manufacturing system components that are developed in the three-level framework (in Table 10). This indicates that a new level that is added to one of the manufacturing system components (e.g. sensor level is added to the physical hardware/carrier component) could lead to a new level being applied to another component/row (e.g. millisecond-second could be added to the time horizon). This might further influence the decision systems (e.g. how the new sensor/real-time level will influence the decision phase of supply chain management or the manufacturing planning and control activity), enabling managers to think ahead and overall.

Such a modification into a smaller time scale could possibly keep in trend with the development of SIMS.

Table 10 – A hierarchical framework for manufacturing system components in different levels.

	Level	***Operational (OP)***		***Tactical (TA)***		***Strategic (STR)***
Physical systems	*Materials/products*	Raw materials; Components; Work-in-process (WIP)		Finished products	Product group/family	Product development
	Hardware/carriers	Machines	Line/Cell	Shop floor	Enterprise	Enterprise; Value chain/network
	Software	Manufacturing execution system (MES)		Enterprise resource planning (ERP)		Strategic enterprise resource management
Decision systems	*Manufacturing planning and control (MPC)*	Production activity control	Material requirement planning	Master production scheduling	Sales and operations planning / Production planning	Strategic business plan
		Purchasing	Capacity requirement planning	Rough cut capacity planning	Resource planning	
	Supply chain management decision phase	Supply chain operation		Supply chain planning		Supply chain strategy/design
	Time horizon	Day, Shift, Week	Week	Week, Month	Month, Quarter	Year

Table 11 – A heuristic hierarchical framework for manufacturing system components in different time horizons.

	LEVEL	*"EXECUTIONAL"*	*OPERATIONAL (OP)*		*TACTICAL (TA)*		*STRATEGIC (STR)*
Physical systems	*Materials/products*	Stock keeping unit (SKU)	Raw materials; Components; Work-in-process (WIP)		Finished products	Product group/family	Product development
	Hardware/carriers	Sensors	Machines	Line/Cell	Shop floor	Enterprise	Enterprise; Value chain/network
	Software	Supervisory control and data acquisition (SCADA)	Manufacturing execution system (MES)		Enterprise resource planning (ERP)		Strategic enterprise resource management
Decision systems	*Manufacturing planning and control (MPC)*	Production activity control		Material requirement planning	Master production scheduling	Sales and operations planning / Production planning	Strategic business plan
		Input & output control	Purchasing	Capacity requirement planning	Rough cut capacity planning	Resource planning	
	Supply chain management (SCM) decision phase	Supply chain monitor & control	Supply chain operation		Supply chain planning		Supply chain strategy/design
	Time horizon	(Real-time) Millisecond-Second	Day, Shift, Week	Week	Week, Month	Month, Quarter	Year

6 Objective, feature and Approach for SIMS

Based on the discussions above, a framework is established regarding important features and pertinent approaches towards objectives in the design and development of SIMS, shown in Table 12.

Both objectives and features for SIMS are divided into two levels, including:

- ***1st level objectives***: quick response to customer needs (i.e. high responsiveness); high variety; low cost; high quality; sustainability;
- ***1st level features***: intelligence/smartness; small scale;
- ***2nd level objectives***: see the design objective tree in Figure 21;
- ***2nd level features***: flexibilization & mobilization; automation & autonomation; digitalization; integration, connectivity, communication and cooperation.

The relationships among objectives, features and approaches (displayed in the italic font style in Table 12) are explained as follows:

(1) Features can be seen either as conceptual approaches towards objectives or objectives to more concrete approaches;
(2) Generally, features serve objectives (vertical direction in the 2nd column from left to right), and approaches serve features (horizontal direction in the 3rd, 4th, 6th-9th rows);
(3) 2nd level features serve 2nd level objectives; 1st level features serve 1st level objectives; and 2nd level objectives serve 1st level features and objectives.

For example, autonomation (or autonomy) as a 2nd level feature is an approach to achieve 2nd level objectives (e.g. autonomous and user-friendly) and further to realize 1st level features (e.g. intelligence) and 1st level objectives (e.g. high responsiveness). Small-scale and intelligence of a manufacturing system, as the 1st level features making up SIMS, form the primary approach/solution to achieve 1st level objectives. Small-scale manufacturing achieve the customer need for product variety or personalized product) though small or one batch size production.

In the horizontal direction, approaches (e.g. in the 6th row: reconfigurable machines, flexible manufacturing systems) towards corresponding features/objectives (e.g. flexibilization) are listed out and categorized according to the hierarchy level in a manufacturing system. For example, reconfigurable machines are considered as an approach in the operational level that is applied to machines and equipment; flexible manufacturing systems are regarded as an approach in the tactical level that is applied to a shop floor; and the concept of agile enterprise is an approach in the strategic level that can be applied to an entire enterprise. A more detailed classification for changeability related to hierarchical product and production levels can be found in [100]. Right to "enterprise" is a broader category named "value network" (in the most right column), and left to "machines & equipment" stands "products & work-in-process (WIP) parts". All of them together with human beings constitute a whole manufacturing system.

6.1 A hierarchical framework of SIMS features and technological approaches towards objectives

Table 12 presents a hierarchical framework of SIMS features and technological approaches towards objectives. For the purpose of work here, a four-level manufacturing hierarchy is adopted for the physical systems in a typical manufacturing system. Different from that in Section 2.7, the cell/line level is excluded and a new level of value network is included.

Table 12 – A framework regarding features and approaches towards objectives in designing and developing SIMS.

		Hierarchy level in a manufacturing system →				
SIMS objectives/features/ (O/F)		**Products & WIP parts**	**Machines & Equipment**	**Shop floor**	**Enterprise**	**Value network**
Level 1 (O)		High responsiveness, high variety, low cost, high quality, sustainability				
Level 1 (F)	Intelligence / Smartness	Smart product with self-managing capability	Smart machine	Smart factory with intelligent modules		Smart value-creation chains
Level 1 (F)	Small scale	Could be small-sized products	Small or one batch size		SMEs	Segmented supply chain
Level 2 (O)		(See the design objective tree in Figure 21)				
Level 2 (F)	Flexibilization & Mobilization	Personalized or customised product	Reconfigurable machines	Flexible manufacturing cells	Agile enterprise	Customized supply chain solutions
Level 2 (F)	Automation & Autonomation	Autonomous parts/products	Autonomous machines	Cognitive factory Unmanned factory		Autonomous transportation system
Level 2 (F)	Digitalization & Virtualization	Digital twin	Direct digital or virtual manufacturing	Digital and Virtual factory	Digital or E-enterprise	Digitalization of value chains
Level 2 (F)	Integration, connectivity, communication and cooperation through IoT, Cloud and Data***					

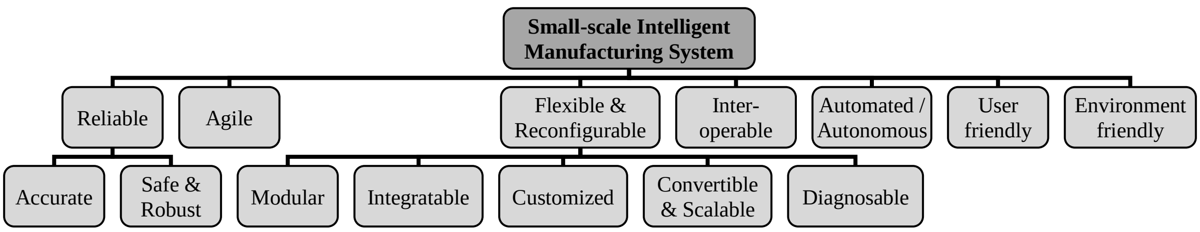

Figure 21 – Design objective tree for SIMS [5].

In the following sections, approaches towards objectives/features are introduced mainly based on literature reviews. While many of the approaches are interrelated in concept, we try to give distinguished explanations with different emphasis or viewpoints.

6.1.1 Towards intelligence/smartness

Nowadays a high degree of product variation and personalization is becoming a prerequisite and production cycles will be radically shortened in a near future world. Industry 4.0 creates the scenario of "smart factory" – the factory of the future. A **smart factory** is more customer-centric, intelligent, flexible and dynamic, and enables the manufacturers to deliver products that meet better individual needs while driving new user experiences [101]. Intelligent components are the results of applying sensor technologies and the ICT progress that ensure the precise operations and flexibility of the manufacturing system. [49]

Smart machines and equipment (including smart sensors, etc.) are necessary components in a smart factory and will have the ability to improve processes through self-optimization and autonomous decision-making [102]. Technological innovation such as sensor technology and semantic technology, enables physical products to be filled with intelligence, sensing- and communication abilities in processes. Such products are called **smart products** [103]. Their unique properties also include context-awareness, pro-activity and self-organizing. Smart products or work-in-process parts are able to make decisions based on different contexts, and even attempt to anticipate the user's activities and choices.

In a smart factory, smart products, sensors, machines and the entire environment are networked with each other through data and information. Manufacturing environments in smart factories should be balanced to support a production model that delivers intelligent and appropriate customization and drives the "mass/individualized customization" reality [101]. Manufacturing processes will be organized within entire production chains from suppliers to logistics to the life cycle management of a product, and closely connected across corporate boundaries [102], forming **smart value-creation chains**. Networked companies in the supply chain make it possible to optimize individual production steps and the entire value chain.

6.1.2 Towards small scale

Small scale can also be applied to/interpreted from different levels:

- ***Product level***: small-sized product (not necessary, just as a current feature of product from additive manufacturing);
- ***Production level***: small batch size or one-off production;
- ***Enterprise level***: small and medium-sized enterprises.

Additive manufacturing technologies such as 3D printing enable small-scale manufacturing, make-to-individual manufacturing and manufacturing-on-demand to become a reality, and can be seen as an alternative to current manufacturing processes [101]. Small-scale manufacturing supported by these technologies enables SMEs to deliver rapid prototyping of often small-sized products and variants and provide special products or irregular parts, eventually to meet an increasing requirement and expectation of more rapid bespoke production globally and locally.

Small scale on the production level contribute to adapting to the new manufacturing paradigm of personalized production. Small and medium-sized enterprises, referring to small scale on the enterprise level, addresses their own challenges different from those facing large companies in the manufacturing sector. In recent years, there have been increasing research work focusing on applying technologies or methods, which have previously been applied to large companies, currently to SMEs. A few are listed in Table 5.

6.1.3 Towards flexibility & mobility

As mention above, approaches towards achieving flexibility and mobility are categorized in different levels.

Reconfigurable machine tools (RMT) are considered as an approach in the operational level that is applied to machines and equipment. RMT is a modular machine with a changeable structure that allows adjustment of its resources, and eventually allows changes in customer demand volume and variety of products [5]. RMT is economical for medium-volume production, high variety in production line, and can fill the gap between dedicated machine tools and CNC techniques

Flexible manufacturing systems (FMS discussed in Section 3.2.3) are regarded as an approach in the tactical level that is applied to a shop floor. FMS is an integrated group of processing CNC machines and material-handling equipment under computer control for the automatic processing of palletized parts [104]. FMS is most suited for the mid-volume, mid-variety production range, and represents a compromise between the high flexibility of versatile job shops and the high production rate of a dedicated mass production system (e.g. transfer lines). FMS is essential to making small-batch production for mass/individualized customization low-cost and profitable [105].

Currently, the trend in FMS is toward small versions of the traditional FMS, called **flexible manufacturing cells** (FMC). Two or more CNC machines are considered a flexible cell, and two or more cells are considered a flexible manufacturing system [106].

The concept of **agile enterprise** is an approach in the strategic level that can be applied to an entire enterprise. Agile manufacturing (discussed in Section 3.4.3) support mass customization, individualized customization or personalized production, cooperate with customers, suppliers and competitors, and bring products (often as solutions to customers' demands) to markets as quickly and cost-effectively as possible. Not only does an agile enterprise offer **customized products**, they also attempt to provide **customized supply chain solutions**.

6.1.4 Towards integration, connectivity, communication & cooperation

In an intelligent manufacturing environment of the future (e.g. SIMS environment), everything will be integrated and connected at different levels. Products including work-in-process parts, machines and equipment, people, and value chain partners communicate cooperate with each other directly.

Real-time information through communication allows manufacturers to be able to collaborate better and more effectively. They will also be able to respond more quickly to competitive pressures, shortening product life cycles, and rising demand for product personalization.

Internet of Things (IoT), cloud computing, Big Data analytics, and mobile technology are some major technological enablers to realize networking, connectivity, communication and cooperation in a manufacturing system or in a supply chain. With the development and maturing of these technologies, manufacturers can response to rapidly changing and specific customer needs and unstable market conditions with more agility than ever before.

6.1.5 Towards automation & autonomy

Automation and autonomy are two of the major indicators of the changes in manufacturing systems (see in Table 2 or Section 3.2). Although technologies such as FMS and CIM provide various advantages, automation itself is not enough to provide competitive advantage [35]. In a modern manufacturing environment, machines should be capable of making decisions and exhibiting autonomous behavior. Autonomation, known as "smart automation", is in a progress to replace automation in the manufacturing related activities starting all the way from design to shipment.

The application of holon technology or agent technology and cognitive technology allows manufacturing systems to react in few seconds to changes in the system environment (disturbances).

Based on connectivity and computing power, manufactured products could be **autonomous products** and incorporate self-reliant or self-governing capability. So do **autonomous machines**. Machines that can behave themselves can not only reduce the costs but also produce the products to be more compliant with the customer specifications. In a **cognitive factory**, each machine and its process are equipped with cognitive capabilities like human behaviors, which enable factory environments to react flexibly and autonomously against the changes [49].

6.1.6 Towards digitalization & virtualization

Integration of the real world into a functional, digital world enables a so-called "**digital twin**" to be created, which allows the real-time representation of processes, systems and entire production shops [107]. Digitalization enables manufacturers to make products more individual and production more efficient and responsive.

A key enabling technology integrating physical products with embedded software and computing power in Industry 4.0 is called "**cyber-physical systems**" (CPS). CPS uses ICTs to monitor and control physical processes and systems [94].

A **digital factory** is the mapping of all the important elements of the enterprise processes by means of ICT [27], and a **virtual factory** is an integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability [28].

6.2 ICT-supported managerial approaches towards objectives

A literature review on the latest managerial approaches (supported by information and communication technology) that can contribute to SIMS objectives is also conducted. A summary is made including objectives and relevant approaches (*in italic*):

- **Supply chain integration** (and collaboration & cooperation): *Information sharing; Resource sharing; Knowledge sharing;*
  - **External integration**: *Just-in-time (JIT) delivery; Vendor-management-inventory (VMI); Cooperative delivery system; Outsourcing logistics (3PL, 4PL);*
    - **Supplier integration**: *Global procurement;*
    - **Customer integration**;
  - **Internal integration**: *Organization culture; Teamwork; Resource sharing; Process improvement; Continuous quality control;*
    - **Process integration**;
    - **Product-process integration**;
- **Supply chain flexibility/agility**: *Product variety management strategy (product- or process-based); Postponement; Dynamic capabilities theory; Customization; One-to-one marketing.*

Integration and agility are two key objectives that managerial approaches aim to achieve. Both integration and agility can be applied to different levels in a manufacturing system and in a supply chain level.

7 Key issues to be solved in developing SIMS

As an emerging manufacturing system paradigm, developing SIMS aims to help SMEs to adapt to the happening Industry 4.0 and the new manufacturing paradigm of personalized production. The new type of manufacturing system should be designed to be able to quickly response to changes in the system environment or changes in the customer demands or other market conditions. Responsiveness has become the focus of market competition and should be a major factor to be considered when designing and developing a new manufacturing system.

The key issues to be solved in developing SIMS could include:

- Manufacturing planning, control and management methods for small batch production;
- Logistics and supply chain management for small batch production;
- Technological approaches for small batch production;
- Logistics systems in geographically-isolated SMEs;
- Barriers to technology adoption in SMEs;
- Performance measurement and management system for SIMS; etc.

8 A case study at Stella Polaris AS

The fisheries, aquaculture and seafood industries have been in a long time generating great value to Norwegian economy and society. Due to high labor costs and increasingly intenser international competition, more and more manufacturing companies in Norway are turning to automation systems and adopting innovation and new technology. This is also not rare in the seafood industry. Despite the commonly small and medium size and distant geographical location of the fish processing plants, the Norwegian seafood industry sector is very modern and advanced in terms of technology and management. Stella Polaris AS, a small to medium sized prawn producer in Northern Norway, is one of those companies that have already established relatively advanced manufacturing systems. In this chapter, a case study based on the manufacturing systems at Stella Polaris is conducted. Some technological innovation and development in the seafood industry are briefly introduced. Future possibilities for improvement in order to further enhance the competitiveness of Stella Polaris and other prawn producers are also discussed.

8.1 Seafood industry in Norway

The Arctic region bears abundant natural resources, including oil and gas, mineral resources, renewable energy, and fishery resources. Around 80 percent of ocean areas in Norway are located north of the Arctic Circle [108]. In terms of value, Norway is the world's second largest exporter of fish and fish products [109]. Seafood products were the second most important export item in 2012 and made up 6 percent of total Norwegian merchandise exports, following the biggest share from oil and gas (70 percent) [109]. In 2009, the Norwegian seafood industry had an annual production of 3.5 million tonnes of seafood which constitutes about 2/3 of national production [109] [110].

The northern part of Norway has been the most important region for the fish processing industry, in which the number of fish processing plants (152) accounted for over half of the total number (285) in 2012 [111]. The fish processing plants are mostly small and medium-sized enterprises (SMEs). According to statistical records from 2004, the number of small and medium-sized plants in Northern Norway (in the Norwegian Raw Fish Organization's area) was around 130, while the number of large plants was around 40 [112].

Owing to the government organizations' supports to guarantee local job opportunities, the authorities' fisheries and business policies, the financial institutions' interests, and the fact that few companies are able to create scale advantages, the changes in the structure of the fishing industry along time have not been significant, unlike other industries [112].

The prawn industry is nevertheless an exception in this case. The majority of Norwegian prawn production exports peeled and frozen prawns. From 1993 to 2003, the number of companies with prawn production has dropped from 26 to 8, and the number of employees from 1500 to 350 [112]. Until 2014, there were in total 6 shrimp processing plants, 4 located in Northern Norway and 2 in Southern Norway [111].

High labor costs and increasingly tougher international competition has led the Norwegian prawn industry to turn to technological innovation to improve the production process. Investments in new technology and automation have resulted in lower costs and increased productivity [112].

Stella Polaris AS is one of the small to medium-sized Norwegian companies in the prawn industry, located in the northern part of Norway with less than fifty employees and focusing on producing cold-water prawns. The company began to replace its production systems with automated ones since 2007 and has succeeded in cost reduction and efficiency improvement.

The significance of such a case study lies not only in providing suggestions to Stella Polaris and other companies in the prawn industry, but also in supporting and enriching the theoretical framework regarding the development of SIMS for the goal of generating a facilitative R&D environment for SMEs to embrace the next generation of innovation and technology.

8.2 Tools and technologies in seafood industry

Price and quality have been two essential factors to be competitive in the market [113], while time-to-market is also becoming a crucial factor nowadays. Applicable technology is a requirement for improving performance. Some vital areas of tools and technologies in the seafood industry are presented in this chapter.

8.2.1 Automation and robotics

Automation and the use of robots or robotic systems are the major enabling technologies in the seafood industry when the goals are reduced production costs and improved product quality and production efficiency. Replacing manual handling with automated handling in the seafood processing also improves working conditions in factories, enhances hygiene standards, and eases conformation to legislation pertaining to seafood processing. Automation and robotics are therefore seen by many enterprises in the seafood industry as a necessity to secure their future survival [113].

In the seafood processing sector, there are different grades of hygiene requirements in different production areas for the equipment, facilities and operators. In hygienic high-risk areas, strict hygiene requirements are set. Robotic systems, like other machines and equipment, should be designed using hygienic design principles, to be easily washable using detergents.

Other than hygienic design requirements, challenges also exist regarding the tough environment (i.e. high humidity and low temperature) in the production areas and finding suitable materials to withstand such an environment. All these challenges lead to the reduced use of robots in the seafood industry and the development of good solutions in automated handling and processing being costly. The seafood industry is yet not at the front of the technological development and generally has a lower degree of automation than many other industries for instance the automotive industry.

8.2.2 Gripping tool

Another challenge exists in the robotic handling of fresh seafood products and other materials/products in special conditions (e.g. the frozen prawn blocks). Robotic systems require end-effectors (i.e. an interface between the robot or programmable arm and the material or product to be handled) to carry out the required handling tasks. The success or failure of an application depends on how well the end-effectors are designed, developed and implemented.

Due to the fact that seafood products are highly variable in shape, size and texture/structure, the automated handling of these types of objects using end-effectors such as gripping tools is a challenging task. The grippers should not only be developed to handle rigid, three-dimensional objects as in most cases, but also developed to handle non-rigid objects.

Besides the applications of robotic systems in direct seafood processing, they are predominantly adopted for material handling tasks such as secondary packaging (case packaging) and tertiary packaging (palletizing). These objects have the same shape and often flat surfaces, and standardized industrial robots and gripping tools are often used for handling these objects. Robots and gripping tools are sometimes replaces by robotic systems which can shift objects in certain directions.

However, even for rigid objects, the automated handling can still be a challenge. This happens in the prawn processing when it concerns feeding frozen prawn blocks to defrosting.

Different handling operations, in combination with different object shapes and product conditions, set different requirement specifications for the gripping tools even though the raw material is from only one species, in this case prawn. Different gripper tool principles are used depending on the object characteristics and the handling task. More gripper tools are needed to increase the use of robots in the seafood industry.

8.2.3 Machine vision and other sensor-related technology

Machine vision is a sector in engineering and is related to computer science, optics, mechanical engineering and industrial automation. Vision as a sensor system is based on the use of camera technology.

Due to the highly variability of the seafood products in shape, size and structure, it poses a major problem for the development of sensor systems. The use of sensors in the seafood processing industry is relatively moderate compared to many other branches of industry. Nevertheless, machine vision has been used for analysing freshness of fish products, grading, sorting according to species or quality, estimating fat contents by automated colour image analysis, and determining connective tissue amounts.

The positive development of machine vision algorithms and sensor-related technology in recent years has resulted in the wider utilization of these technologies in seafood processing applications and allows for development of more automated fish processing plants.

8.2.4 Control system

Modern automated processing plants require suitable control systems. New low-cost computer technology is one of the reasons for the considerable development of control systems during the laste decades, to become relatively cheaper and have a far higher capacity for data processing. Production control systems should be based on the principles of flexible and reconfigurable systems (open-architecture control). If the seafood factory of the future is close to being a fully automated processing plant, a considerable effort regarding further development of the control systems is still required.

8.2.5 Electronic information system

Sectors of the shrimp industry have developed an electronic information system that can provide customers/consumers more information about shrimps. The aim is to create added value for the customer by offering supplementary information about the product, which is not normally possible on the product packaging. Each product is given a unique batch number which the consumer may enter into the website to access more information. It is suggested to use the QR code which can simplify this further. This will enable the producer to customize the information for the shrimp product that is being eaten, which will be directly available to the consumers [114]. Each factory may develop its own set of rules concerning which product information will accompany the product. The system has now been tested, but practical implementation in the companies remains to be done.

New technologies such as Internet of Things could be taken under consideration picturing a future manufacturing system.

8.3 Prawn production system at Stella Polaris AS

Fig. 1 illustrates an overview of the production processes at Stella Polaris AS. After fresh prawns have been caught and hauled on board the fishing vessels, they are frozen and packed in blocks and then stacked on pallets. Most of the raw materials are landed directly at the production plant and delivered to the raw material warehouse for temporary storage. The prawns to be further processed are transported currently by forklifts to be thawed and then to be cooked. After cooking, the prawns are peeled and cleaned for shells and heads. Then the prawns are frozen with a protective layer of water (glazing) to prevent drying out and freezer burns. Afterwards, the glazed prawns are packed in plastic bags (as primary packaging) and the bags are packaged in cardboard boxes (as secondary packaging). Then the boxes are then palletized (as tertiary packaging) and conveyed to the cold storage warehouse for finished products.

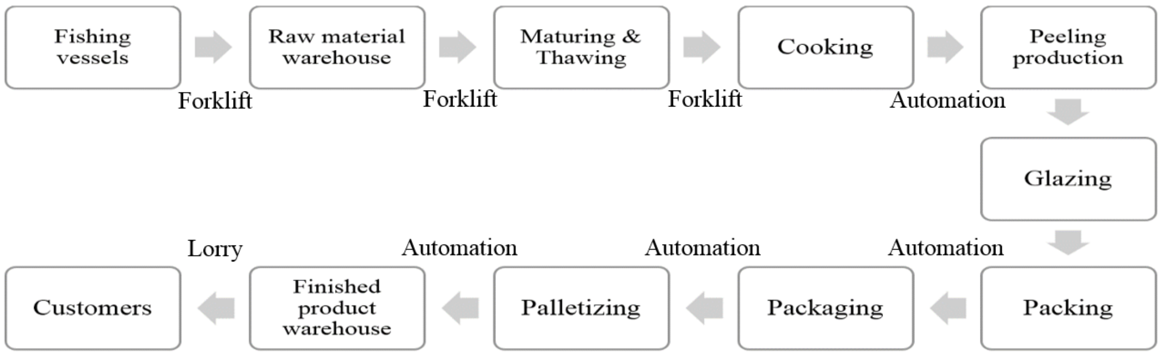

Figure 22 – Prawn processing in a prawn producer.

High production capacities, more stringent quality demands, and pressure on costs require ever higher degrees of automation and intelligence for operation systems. The manufacturing systems at Stella Polaris are very modern and advanced in terms of technology and management. All the way from the cooking equipment to the warehouse for finished products, including the peeling machinery equipment, the glazing equipment, the packaging system, and the palletizing system, the process is completely automated and streamlined. The integration of all machinery equipment and automation systems into a whole system is an essential precondition for efficient operations. Automated and integrated conveying and material handling systems play a role in assuring smooth production and processes.

8.4 Improving the existing production system

8.4.1 Towards responsiveness or agility

The manufacturing system should be designed to be able to quickly response to changes in the system environment or changes in the customer demands or other market conditions. Responsiveness has become the focus of market competition and should be a major factor to be considered when designing and developing a new manufacturing system. This is in agree with the company's strategy focusing on achieving agility. This is more business-oriented. An agility enterprise aims to deliver customized products (packaging in this case) and customized supply chain solutions.

8.4.2 Unmanned factory

One scenario for implementing the new type of manufacturing system is an "unmanned factory", in which the managers and worker do not need to go to the plant and could stay somewhere else while controlling the plant operation, with the application remote monitoring and control and mobile technology

8.4.3 From automation to autonomous

Based on connectivity and computing power, manufactured products could be **autonomous products** and incorporate self-reliant or self-governing capability. So do **autonomous machines**. Machines that can behave themselves can not only reduce the costs but also produce the products to be more compliant with the customer specifications. In a **cognitive factory**, each machine and its process are equipped with cognitive capabilities like human behaviors, which enable factory environments to react flexibly and autonomously against the changes [49].

9 Conclusions

In this project work, an extensive literature review on manufacturing systems was conducted (see in Chapter 2 and Chapter 3), covering diverse aspects from definition, components, levels, types of process, progresses in manufacturing methods including both technological and managerial approaches, etc. The literature study has helped to better understand the background, purpose, and benefits of developing SIMS, which are described in Chapter 4. In Chapter 5, a novel architecture for defining a manufacturing system from the supply chain perspective is built. In Chapter 6, a hierarchical framework of SIMS features and technological approaches towards objectives is developed. Managerial approaches towards some of the objectives are also listed. Key issues to be solved in developing SIMS are discussed in Chapter 7. Besides the theoretical frameworks developed for SIMS, a case study is discussed in Chapter 8, regarding the possible implementation of SIMS at Stella Polaris AS, a prawn producer located in the northern part of Norway.

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