# Scope of Work

**Title of the Thesis:**
*Reference model for production systems*

| | | | |
|---|---|---|---|
| **Inv.- Nr.:** | 2019/47696 | | |
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| **Issued:** | 01.04.2019 | **Submitted:** | 09.09.2019 |

**Motivation:**
Nowadays the industry is evolving constantly in different aspects and factories need to be prepared to changes. Different drivers lead to a change in the production such as technological evolution, crisis, process reviews, mergers or more. Due to this issue, most of the production plants are pushed to improve their production systems to optimize and update the best resources and machines. A model to recognize most of the manufacturing plants could be helpful for the future in the moment to evaluate change management. Increasingly complex factory systems lead to insufficient transparency of the cause-effect relationships in production. Understanding these, however, is the basis for successful planning activities like change management. Although production systems have uniform elements and structures, there is currently no generally valid representation of them. The diversity and complexity of the different production plants is another incentive to try to identify and clarify the difference between each other.

**Objective:**
The aim of this master thesis is to develop a reference model which shows and explains the production plant with the different areas from an abstract and complex perspective. For the accomplishment of this goal, first must be described how are the manufacturing systems, the different types of production systems and how are related to the different areas. The main aspects from a production plant are the different flows like material and energy flows, personnel and information flows and IT interfaces. The idea is to standardize the production model with the help of literature research and case studies for helping to visualize what a production plant needs easily for different companies. The model will be developed based on the current state of the literature and completed and validated by small assembly plant. Once the reference model is developed, it will be easier to support planning activities such as change management.

**Procedure and working method:**

- Literature research and definition of production
- Literature research and identification of different types of production
- Literature research of production systems and reference models
- Derivation of potential deficits and development of a reference model
- Validation of the reference model through expert interviews

**Agreement:**

Mit der Betreuung von Herrn (B.Sc.) Luis Alcalá-Santaella Martínez durch Herrn M.Eng. Harald Bauer fließt geistiges Eigentum des *iwb* in diese Arbeit ein. Eine Veröffentlichung der Arbeit oder eine Weitergabe an Dritte bedarf der Genehmigung durch den Lehrstuhlinhaber. Der Archivierung der Arbeit in der *iwb*-eigenen und nur für *iwb*-Mitarbeiter zugänglichen Bibliothek als Bestand und in der digitalen Studienarbeitsdatenbank des *iwb* als PDF-Dokument stimme ich zu.

Garching, den 09.09.2019

Prof. Dr.-Ing. Gunther Reinhart M.Eng. Harald Bauer M.Sc. Luis Alcalá-Santaella

# Abstract

With the evolution of the manufacturing industry and the necessity of a general representation of a production system, a reference model of production systems focused on assembly processes to easily visualize a manufacturing system was developed. Manufacturing companies can identify and model their own production system with this reference model, and once there is a model done, the company can be flexible and be prepared to the different changes in the industry or factory.

For the development of this model, it was necessary to do a research about the current models about factory systems and seeing the gap of literature, the reference model was created with different modelling methods, but focused mainly in the Product, Process and Resource model as well as Value Stream Mapping. For the understanding of this model, the basic principles of manufacturing are described with the different areas as well as logistics, maintenance, IT interfaces and factory planning. Also the different modelling methods and the purpose of this modelling are explained. The last chapters explains the reference model in detail, with figures to understand them and the application of this model to a case study for the validation of the model. Finally there is a summary of the work, with some possible future researches on the topic.

# Table of Contents

# I List of Abbreviations

| | |
|---|---|
| THS | Transport, Handling and Storage |
| CIM | Computer-Integrated Manufacturing |
| SCM | Supply Chain Management |
| MRP | Material Requirements Planning |
| CRP | Continuous Replenishment Program |
| WIP | Work in Progress |
| MTO | Make to Order |
| MTS | Make to Stock |
| JIT | Just in Time |
| CAD | Computer-Aided Design |
| CAM | Computer-Aided Manufacturing |
| SMED | Single-Minute Exchange of Dies |
| CRP | Continuous Reconfiguration Planning |
| ExMS | Extended Manufacturing System |
| StCM | Structural Complexity Management |
| DSM | Design Structure Matrices |
| DMM | Domain Mapping Matrices |
| MDM | Multiple Domain Matrices |
| SysML | Systems Modelling Language |
| UML | Unified Modelling Language |
| PPR | Product Process Resource |
| OPM | Object Process Methodology |
| ERP | Enterprise Resource Planning |
| EWM | Extended Warehouse Management |
| MES | Manufacturing Executive System |

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# 1 Introduction

## 1.1 Motivation and Objectives

Nowadays the industry is evolving constantly in different aspects and factories need to be prepared to changes. Increasingly complex factory systems lead to insufficient transparency of the cause-effect relationships in production. Understanding these, however, is the basis for successful planning activities like change management. Manufacturing flexibility has been the key for many years for manufacturing science and operations management for being aware of changeability (TONI & TONCHIA, 1998). Changeability of the manufacturing systems is needed due to frequent changes in market requirements and product demands, and this provides an advantage for industrial enterprises. To perform the changeability efficiently and effectively, would be necessary to plan and implement the reconfigurations of manufacturing resources (DAŠČENKO, 2006). (WIENDAHL & ZÄH ET AL, 2017).

The research through modelling manufacturing systems was necessary, due to its importance to change management regarding all these changes during the last years. It changed our focus from static flexibility to dynamic flexibility, working with unpredictable future challenges, like for example sales volume fluctuations, new customer requirements or even new technologies. Therefore, with modelling is easier to identify topics like modularity, compatibility and universality of factory systems and their elements (DAŠČENKO, 2006). It is important to understand the manufacturing system to try to implement these reconfigurations, because it is relevant to understand the three pillars of production, manufacturing resource, manufacturing product and process, that will be explained in chapter 3, but also it is important the influencing factors and the manufacturing planning process (PLEHN, 2017).

Different drivers lead to a change in the production such as technological evolution, crisis, process reviews, mergers or more. Different topics like technology and product innovation, varying demand, shifted product mix, continuous improvement initiatives, or regular substitutions of outworn equipment and machines are the reason of a lot of changes in manufacturing systems. Production systems are related with different areas and are influenced from these changes also. This complex network of elements interconnected needs to be taken into account for the successful outcome of the company. Elements like infrastructure or technological dependencies can even influence on business actions like in logistic or strategical business plans (PLEHN, 2017).

Due to this issue, most of the production plants are pushed to improve their production systems to optimize and update the best resources and machines. Although production systems have uniform elements and structures, there is currently no generally valid representation of them. A model to recognize most of the manufacturing plants could be helpful for the future to evaluate change management. The diversity and complexity of the different production plants is another incentive to try to identify and clarify the difference between each other.

The aim of this master thesis is to develop a reference model which shows and explains the production plant with the different areas from an abstract and complex perspective. For the accomplishment of this goal, first must be described how are the manufacturing systems, the different types of production systems and how are related to the different areas. The main aspects from a production plant are the different flows like material and energy flows, personnel and information flows and IT interfaces and how they are interconnected to the assembly station. The idea is to standardize the production model with the help of literature research and validate it in a production plan, for helping to visualize what a production plant needs easily for different companies.  The model could be a tool to use in the future, for any kind of production system, where they will start to plan or identify its own production system, and see if they need to add or focus in any area or element. Once the reference model is developed, it will be easier to support planning activities such as change management.

## 1.2 Structure of the Thesis

The structure of the thesis is based on the achievement of the reference model and once it was developed, was required to structure the thesis in the best possible way to understand the basic background necessary for the model and the gap of this topic in the literature. As it is shown in Figure 1-1,  the thesis is structured first with a basic introduction of different relevant topics for the model, like manufacturing, intern logistics and maintenance. After that, it is important to explain what is modelling and which is the purpose of it. In this section, the different modelling methods that have been developed during the years will be explained and describing in detail the ones which will be relevant for the reference model. Those would be the definition of metamodel and the techniques of Product, Process and Resource modelling and Value Stream Mapping. Following this chapter comes the state of research, where different references are explained and compared with the requirements of the reference model that will be developed. In this section, the gap of the literature for our goal will be introduced and how some documents helped to the development of this work. Once it was everything explained for the clear understanding of the model, the reference model since the beginning of the work is explained, with the requirements and procedure that were followed. After that, the development of the reference model appears and with it the first overviews of the reference model, explaining the structure and each area more in detail. Finally for the validation of the model, this was applied to a case study which is described including the improvements that were done because of it. At the end a summary of the thesis and future possible researches continuing with this model are presented.

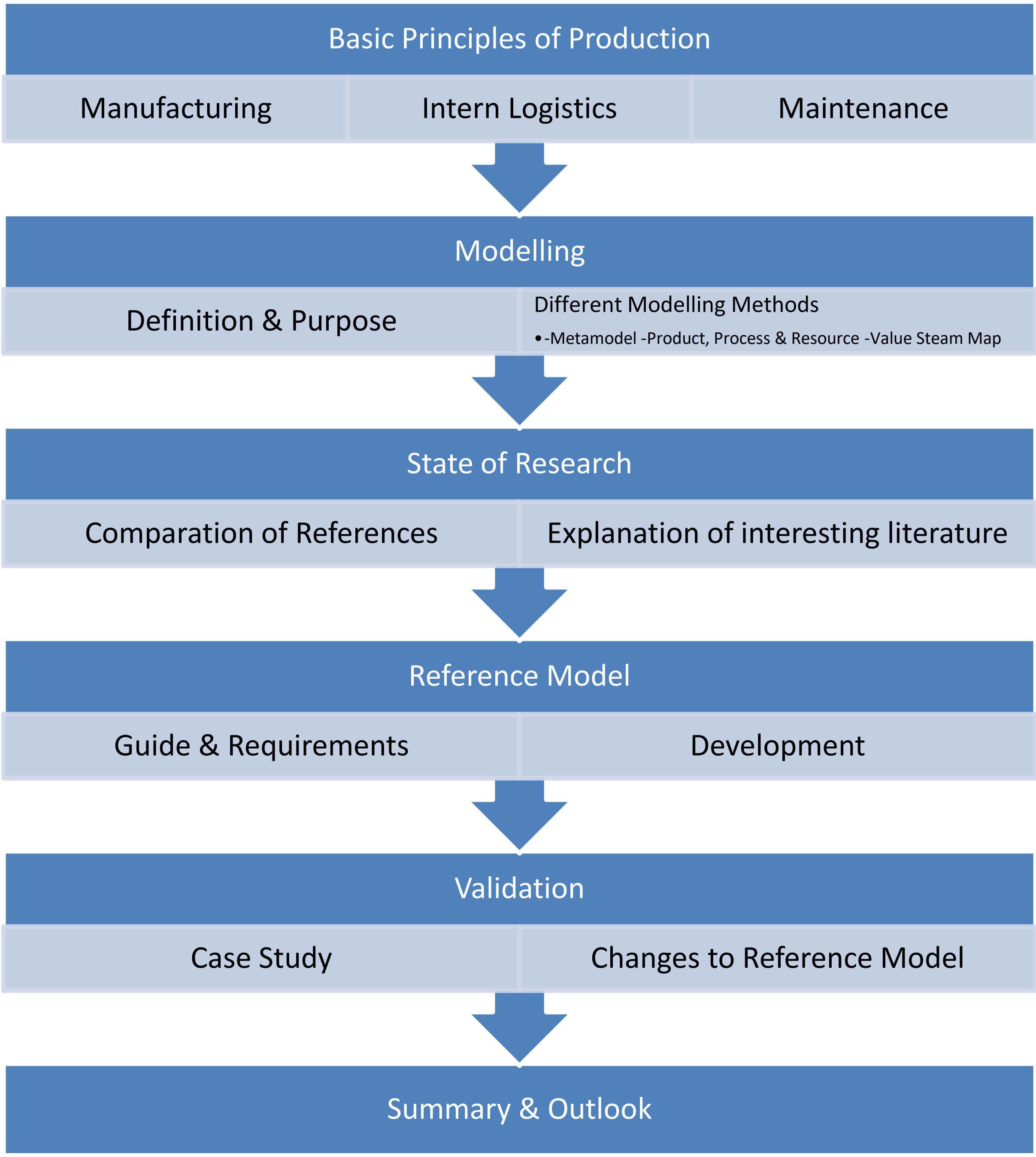



*Figure 1-1 Structure of the thesis*

# 2 Basic Principles of Production

In order to understand the reference model for production systems, it is important to know the basic principles of production. Basic background of manufacturing, logistics and maintenance is relevant for this thesis and therefore they will be explained in this chapter.

Manufacturing companies manufacture and supply products with the coordination of procurement, production, sales and distribution departments and with the infrastructure and production facilities.

"Production facilities, workshops and factories are basic tools used by businesses to add value" (SCHENK ET AL., 2010). Figure 2-1 illustrates the production facility's position in the enterprise environment.

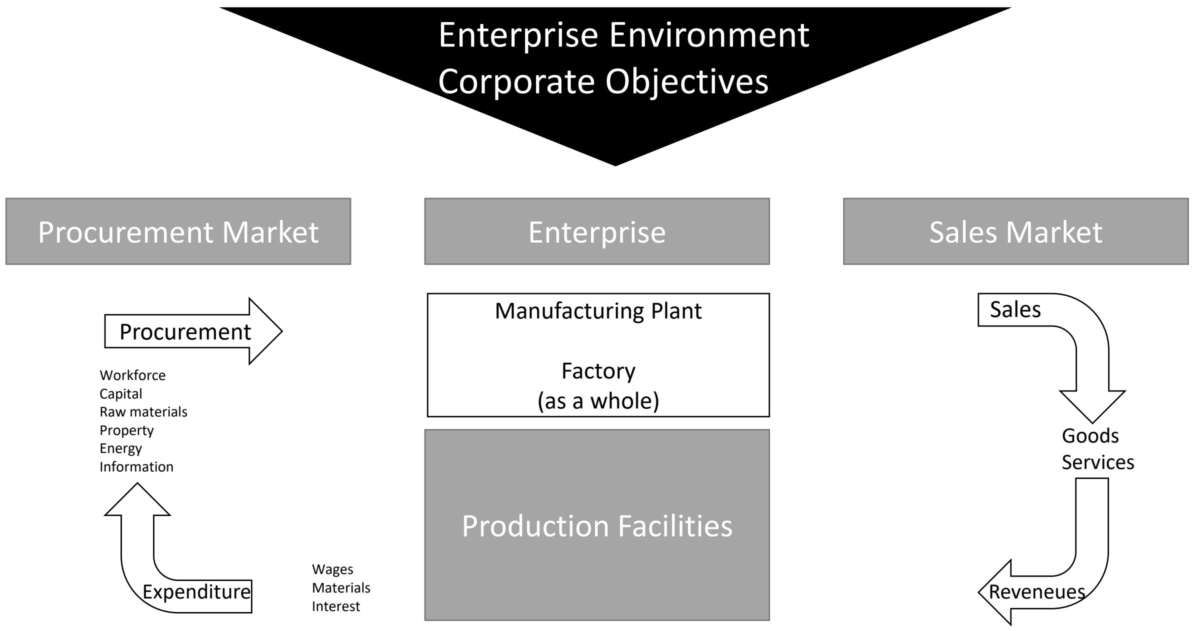



*Figure 2-1 Production facilities as part of an enterprise (SCHMIGALLA, 1995)*

## 2.1 Manufacturing

"Manufacturing is the backbone of any industrialized nation" (SINGH, 2010, P.14). Manufacturing is a big topic in all the ways and it is important to understand all kind of areas inside production for understanding and optimize the processes. This topic covers important areas like manufacturing processes, tools and equipment, technical topics in the industry and even safety rules to avoid accidents. (SINGH, 2010, P.14). The main goal is to produce goods, articles or components which provide services to the people for different activities. It generates value for the materials.

Manufacturing comes from the Latin word manufactus, and this means made by hand. Nowadays this concept means making products from raw material with the help of hand tools, machinery or computers to do some processes like welding. Consequently, manufacturing is a deep study of how are the processes to make parts and how to assemble them in machines or manually. (SINGH, 2010, P.15)

On the same side, the word "production" has the same meaning but it is focused more on the transformation of materials, services, rights and information in the sense of operational value creation (DYCKHOFF 2003, P. 3). Thanks to the supply of material obtained by procurement department, the manufacturer company creates value converting these input factors in higher value goods for the sales department (SCHUH & SCHMIDT 2014, P. 2). Normally is a coordination of different activities interconnected creating a chain of different processes like “order processing, product design, design and manufacturing of tools, die, mould, jigs, fixtures and gauges, selection of material, planning, managing and maintaining control of the processes, production, and reliable quality of processed product in a systematic and sequential manner with proper coordination, cooperation and integration of the whole manufacturing system that will lead to economical production and effective marketing of proposed product in the minimum possible time” (SINGH 2010, P.24). As it is shown in Figure 2-2, the input factors are modified through different processes to create an output with higher value and also some wastes and consequences.

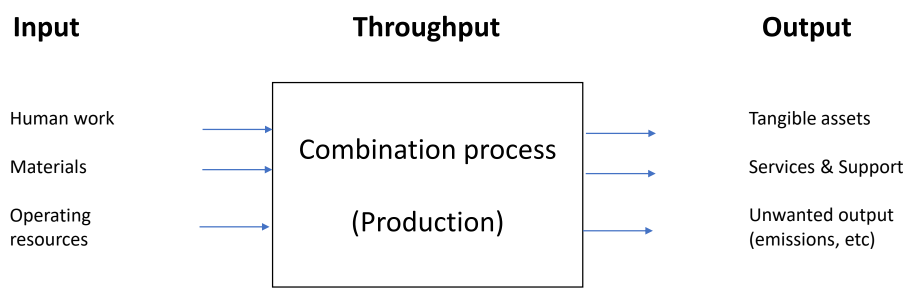



*Figure 2-2 Production as combination process (BLOECH ET AL. 2014, P.3)*

### 2.1.1 Manufacturing Process

The Manufacturing System needs a lot of different activities, and in this case, it is possible to see interconnected activities with each other but there are also independent activities that are necessary for the production. This system starts demanding inputs for developing the processes and deliver the product to the customer. The main purpose always is to get all the processes in an efficient way with a minimum possible time and costs, and the best possible result. In the manufacturing process is not included the THS (transportation, handling and storage) because it is not related with actual process of transforming the product. The manufacturing process is directly related with the modification of forms or dimensions (SINGH 2010, P.24)

The first steps is to get an idea about the market, what they are interested on because of the process design phase. Depending on the customers' forecast and the competition, the products will be designed in different ways taking into account a lot of variables. After the design phase is finished, with a continuous improvement during the phases from different topics like aesthetic, functional, material selection, etc…it will continue with the production of drawings of the product and the bill of materials. This is important because the company will decide which components will be outsourced or produced in the factory. Next stage would be process planning, selecting basically every kind of process for the manufacturing, like dies design, jigs and tools needed, the parameters for each machine and programming. The real production comes next which is done in the shop. Depending on the layout, the manufacturing processes will be really different, therefore there is a big influence in the layout with the cost and time of the processes. All these processes needs to ensure a well material flow with all the connected activities, between material and machinery, personnel, safety, quality controls and more. The engineers will take a big role in the organizational function for the production. (SINGH 2010, P.24). Once all the components are finished in our process, the assembly process starts to get the finished product. (SCHENK ET AL., 2010)

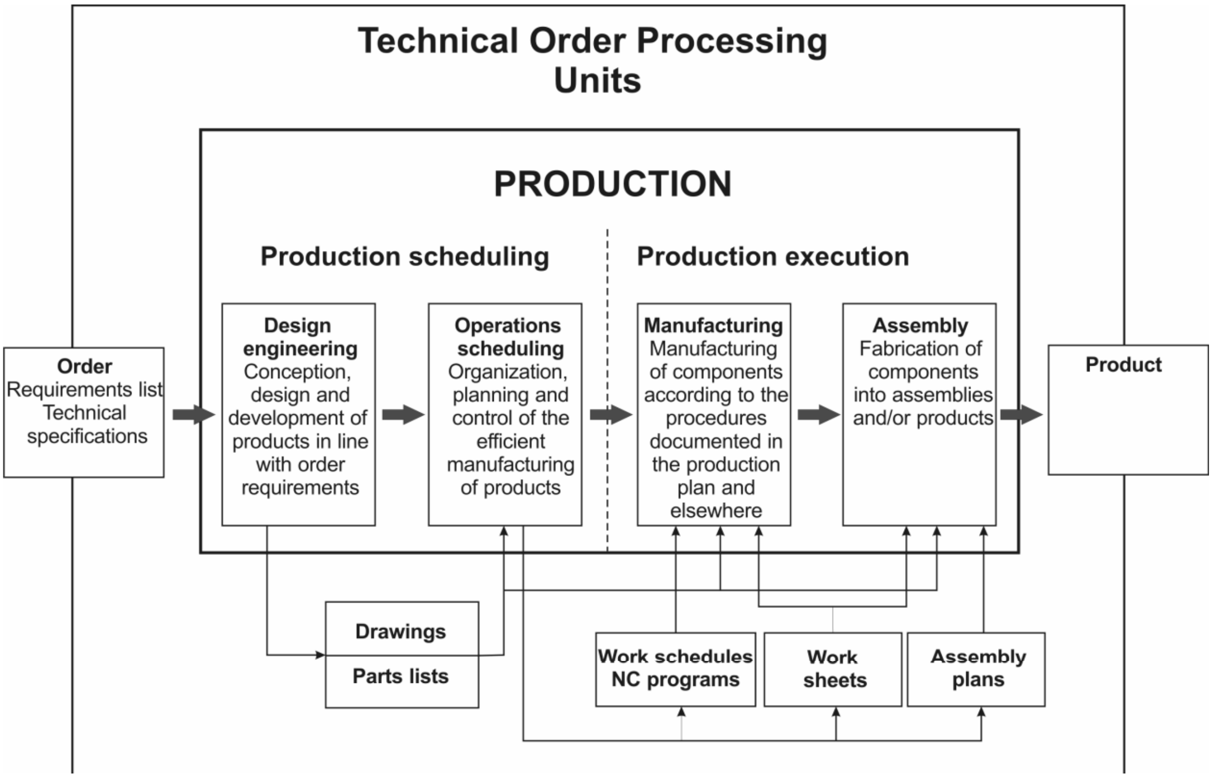



*Figure 2-3 Manufacturing System Processes (SCHENK ET AL., 2010)*

In the Figure 2-3 is shown a similar timeline for the manufacturing system processes.

A similar structure is shown in the Figure 2-4, where it is focused more on the product elements and which processes are required for the creation of it. The product elements would be unfinished part/purchase part, individual part, assembly, main assembly, product and on the other side the production steps would be prefabrication/manufacture of parts and assembly (component assemblies, main component assemblies and final assembly) (SCHENK ET AL., 2010).

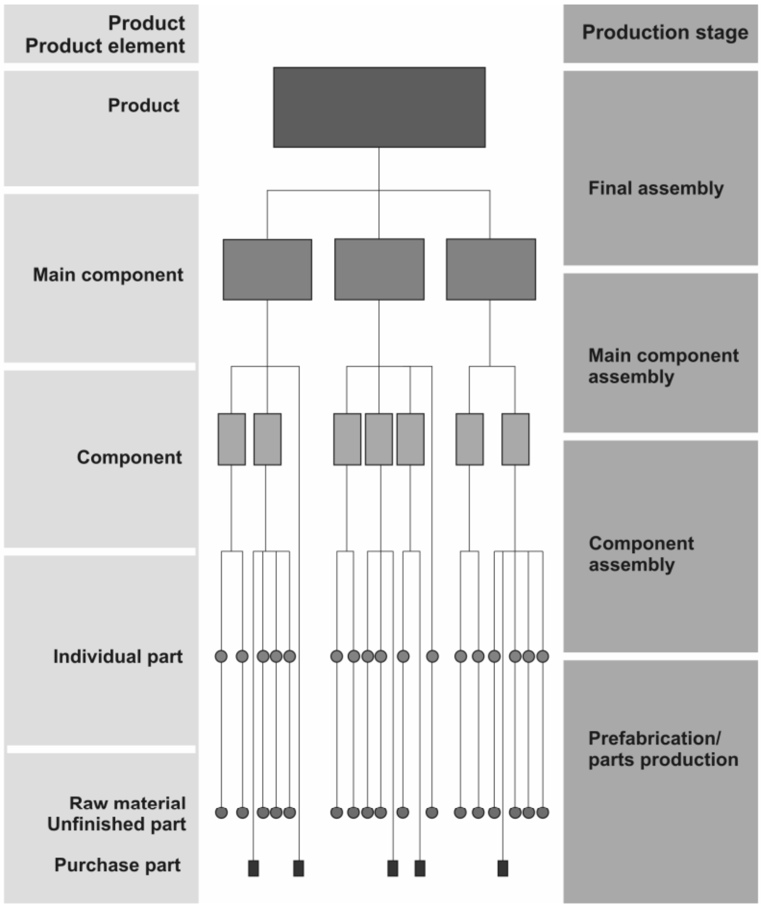



*Figure 2-4 Product structure and manufacturing stages (GRUNDIG 2000, P. 67)*

As it is shown in the process planning phase, there are a lot ways of planning the same production of a product, therefore the selection of the corrected and optimized processes is important and it depends in a different factors also like volume of production, characteristics of the components, technical viabilities, economic issues and quality desired (SINGH 2010, P.24).

## 2.1.2 Factories

The flexibility is one of the main topics for the factories due to changeability during the years and one of the reasons of the thesis. Factory is a building or a group of buildings where industrial operations are done with the idea of making profit with the production of goods. The layout is important in here because the organizational areas in the building are relevant for the different processes and the facilities must me planned for the optimized result. Workstations, production machines and operational facilities are parts of a factory. Each factory is different depending on their characteristics and can be categorized like in the figure below (SCHENK ET AL., 2010).

| Characteristic | Attributes | | | | | |
|---|---|---|---|---|---|---|
| Enterprise size | Small enterprise | Small and medium-sized enterprise | Large enterprise | | | |
| Product size | Micro | Small | Medium | Large | | |
| Production process | Continuous | Batch | Combined | | | |
| Investment period | Short-term | Medium-term | Long-term | | | |
| Location strategy | Local | Regional | National | Global | | |
| Location changes | Mobile | Permanent | Combined | | | |
| Factory orientation | Process | Product | Workforce | Buildings | | |
| Type of production | Make-to-order production | Small batch | Medium batch | Mass | | |
| Value-added stages | Marketing | Research/ development | Procurement | Production | Sales & Marketing | Service |
| Operator models | Buy | Rent | Lease | | | |
| Production stages | Single part | Structural elements, components | Assembly, system assembly | Units (vehicles) | Plant systems | |
| Networking | Autonomous factory | Networked factory | Competence networks | Virtual factory | | |
| Use | Reuse | Further use | Recycling | Disposal | | |

Example: standardized factory

*Figure 2-5 Morphology for determining factory types (SCHENK & WIRTH 2004, P. 18)*

Each factory and production facility are unique because each one is different in different aspects like its human resources, products, processes, systems, function, dimensions, structure, layout, profitability and corporate philosophy.

## 2.1.3 Push / Pull Manufacturing

The difference between these two concepts is relevant in the manufacturing industry because each production system requires different steering logic. Deciding as a manufacturer which process to use is a difficult task because it will depend in different variables like what the customers want and when, and the company needs to find what is the best for them. Sometimes the best is to do a combination of both like in Supply Chain Management (SCM), and the technology nowadays enables the companies to switch easier from one to another. ("PUSH-PULL MANUFACTURING | LEAN MANUFACTURING" 2019)

### 2.1.3.1 Push

Push manufacturing is when the schedule work release is based on demand (HOPP & DUENYAS, 1998). For example, when using a demand forecast that works with the Material Requirements Planning (MRP) where with the lowest possible inventory, it is a safe procedure because of the availability of all the materials. The accuracy of the forecast is not perfect and therefore there is usually also an excess of inventory. ("PUSH VS. PULL MANUFACTURING: IS A KANBAN PULL SYSTEM RIGHT FOR YOUR COMPANY?" 2019) During this process, there are a lot of work in progress (WIP) and the environment is distinguished for long lead times and known as make to stock (MTS) manufacturing. Materials, parts or products are transferred to the next stage whenever the current process was finished. One of the advantages is processing large batches of units and following next processes based on customer demand ("PUSH-PULL MANUFACTURING | LEAN MANUFACTURING" 2019).

### 2.1.3.2 Pull

Pull manufacturing systems is waiting until there is demand. The authorize work is based on system status (HOPP & DUENYAS, 1998). If there is a specific customer order, the company will manufacture the goods. This system works better when the demand is stable and high in a small variety of products. Kanban will be an important process in this kind of system because it is in charge of the work orders basically and it is controlling all the material flow of the materials through the different workstations ("PUSH VS. PULL MANUFACTURING: IS A KANBAN PULL SYSTEM RIGHT FOR YOUR COMPANY?" 2019). Pull manufacturing means Make to Order (MTO), where the production is based on actual demand. In this case, this kind of supply can be related to Just in Time (JIT) and Continuous Replenishment Program (CRP). The products are supplied at a higher speed and with short lead times, keeping the inventory low. ("PUSH-PULL MANUFACTURING | LEAN MANUFACTURING" 2019). Basically the upstream task requires materials for the next production process and the pull system will provide these new materials. Overproduction will not be possible due to that new parts are only produced in the takt time and there is actual demand (KLUG 2010, P. 258). Therefore, this makes that the takt time is the pacemaker of the entire system, and also promises that the customer demand will be successfully accomplished (WOMACK & JONES 2003).

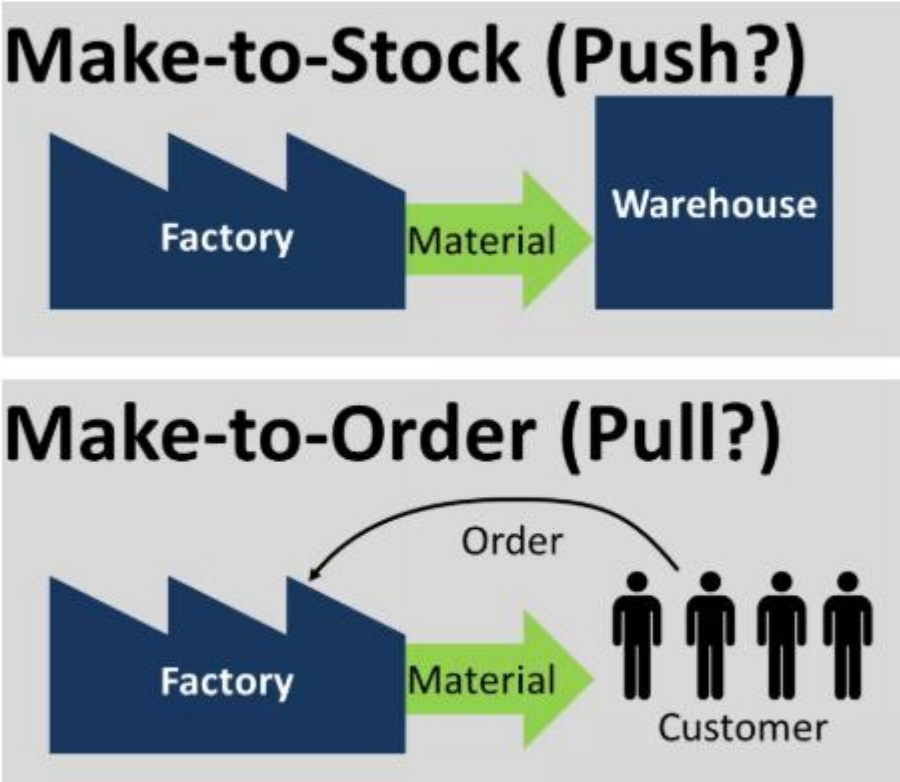



*Figure 2-6 Difference between Push/ Pull (ROSER, 2019)*

**Kanban**

Inside pull manufacturing, Kanban is a key element and this is a Japanese word that means "card you can see" and comes from the Toyota production system. To control a pull manufacturing system, Kanban facilitates to link processes between the manufacturing order and the workstation (ERLACH 2010, pp. 190-193). Kanban is "a signal that gives an instruction to get, move, produce, order, or take some other activity with production materials". Kanbans are always showing when to order, what, how much and where to order it from ("KANBAN: MANAGE INVENTORY WITH THIS LEAN TOOL" 2019). KANBAN's goal is to decrease the time and effort due to the repetitive processes (SCHENK ET AL., 2010).

| Part Description | | | | Part Number | |
|---|---|---|---|---|---|
| Smoke-shifter, left handed. | | | | 14613 | |
| Qty | 20 | Lead Time | 1 week | Order Date | 9/3 |
| Supplier | Acme Smoke-Shifter, LLC | | | Due Date | 9/10 |
| Planner | John R. | Card 1 of 2 | | | |
| | | Location | | Rack 1B3 | |

*Figure 2-7 Kanban example ("KANBAN: MANAGE INVENTORY WITH THIS LEAN TOOL", 2019)*

### 2.1.4 Computers in Manufacturing

During the years, the importance of computers and technology have been increasing really high due to all the complexity products, increasing speed, flexibility of shapes for the customers, productivity and costs, etc… As it will be explained later, even in our model is mentioned different technologies that are necessary for a manufacturing system.

Since 1960, computers have been used at first in only areas like accounting, controlling or inventory, but it was spread fast to different areas like production and logistics, but these machines have been developed a lot during the years and the technology for the manufacturing system is important for the quality of the product and the costs of production. An important step was the introduction of computer applications like Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), and the combination of these two together efficiently improved the manufacturing system process in different aspects. This interfacing is known as CAD/CAM. It involves the flow of information in both directions. This short introduction about the computers in manufacturing is an example of how technology and the new techniques with all the information flow and the different technologies creates new and better products that could be produced faster and cheaper (SINGH 2010, P.26).

### 2.1.5 Types of Manufacturing

It is necessary to identify the type of manufacturing in a production system. Generally there are four different types of production systems, but there are different opinions to this topic, which will be explained in this section. The company needs to decide which type of production want to use because it will depend in different aspects like the demand of the customers, the type of product being manufactured, the supply of raw materials and how continuous is the process (BHASIN, 2018). Each production system can use different automated levels and with different machines (COOPER, 2015).

#### 2.1.5.1 Job shop production

Job production is generally done for luxury and customised products, producing a small amount of customised products with high skill workers in different aspects and it is characteristic to share the resources with a low degree of repetitions (COOPER 2015). It comprises an operator or group of operators to work upon a single job. Here the manual work sometimes is important and also the customer service and management are relevant for the production. A good example of this could be Harley Davidson Products (big variety of complements) or Dell products (each laptop is different) (BHASIN 2018). Demand is unpredictable and the quantity involved will be small (SINGH 2018).

### 2.1.5.2 Batch production

Batch production system is used for a variety of products with a variety of volumes. Depending on the orders or on the demand forecasts, the production schedule will be decided (SINGH 2018). It is the most common type in the industry and makes groups of identical products (COOPER 2015). They are used to produce batches of small quantities of output and each batch has its own specifications (TANENBAUM & HOLSTEIN 2012). When a batch is finished, the same manufacturing facility is used for another batch. Sometimes batches can be periodical (repeated after some intervals) or can be used only once (SINGH 2010, P.15). Whenever the manufacturer starts with the production, he knows the number of units to produce in the batch. This production system is used in industries like medicines, hardware and consumer durables (BHASIN, 2018).

### 2.1.5.3 Mass production

Mass production is for products with less variety but with a large quantity of standardized products. The assembly lines are inside this group with workstations in sequence. For this author, the mass production system is divided in continuous type which are production systems without interruptions and also the assembly line production system (SINGH 2018). For this kind of production, it is needed a huge investment cost in special machines and automation with the purpose of producing a large number of identical products with the best possible efficiency (SINGH 2010, P.15). It is used for identical products, to reduce the prices of production such as cars, electro domestics… (COOPER 2015) The investment on the facility is for reducing the price in the long term due to the high volume. The tasks of the operators are segmented in small groups to perform better and more efficiently (TANENBAUM & HOLSTEIN 2012).

### 2.1.5.4 Project type

Last type of production that will be mentioned is the project type or “one-shot” system. This kind of production is for a building, a ship, or the prototype of a product where the resources will be used only for once (TANENBAUM & HOLSTEIN 2012). The tasks will be not repetitive because every project is unique. A lot of resources like workforce and big facilities could be required and the difficulty is that there is no too much guidance for the project from products done in the past (SINGH 2018).

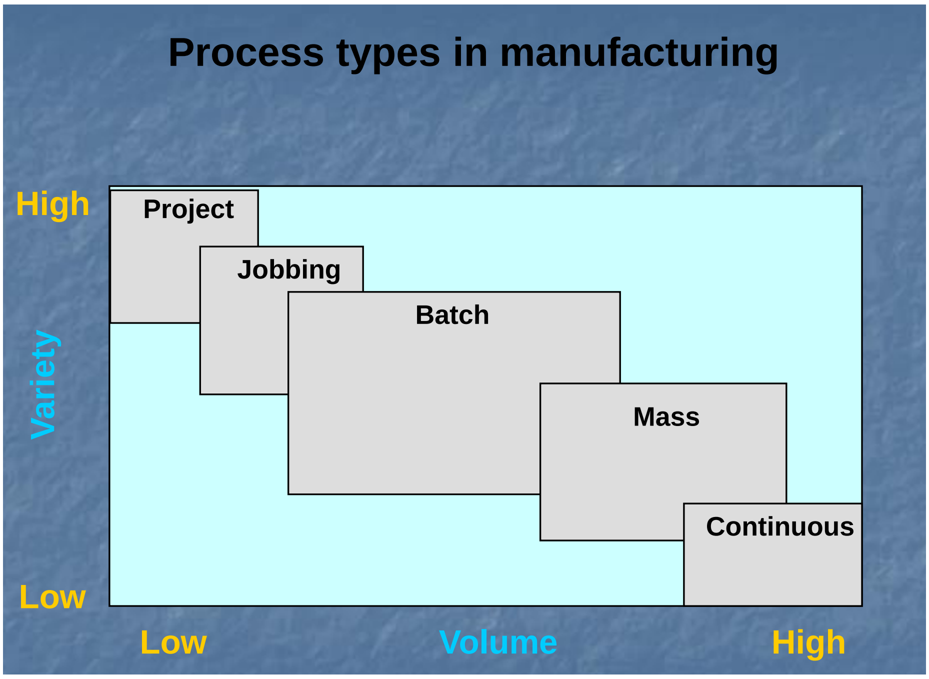



*Figure 2-8 Types of Manufacturing (COOPER 2015)*

## 2.1.6 Production Systems

This section is an introduction to the production system concepts and classification and also some different concepts that are relevant to the reference model. As it is shown in Figure 2-9, regarding to machines classification, production systems are classified in reliable and unreliable machines. Most of the large volume manufacturing companies have breakdown machines and with finite buffer capacities (JINGSHAN LI 2009). In the Figure 2-10 , there are some different classification of production systems regarding to the material flow.

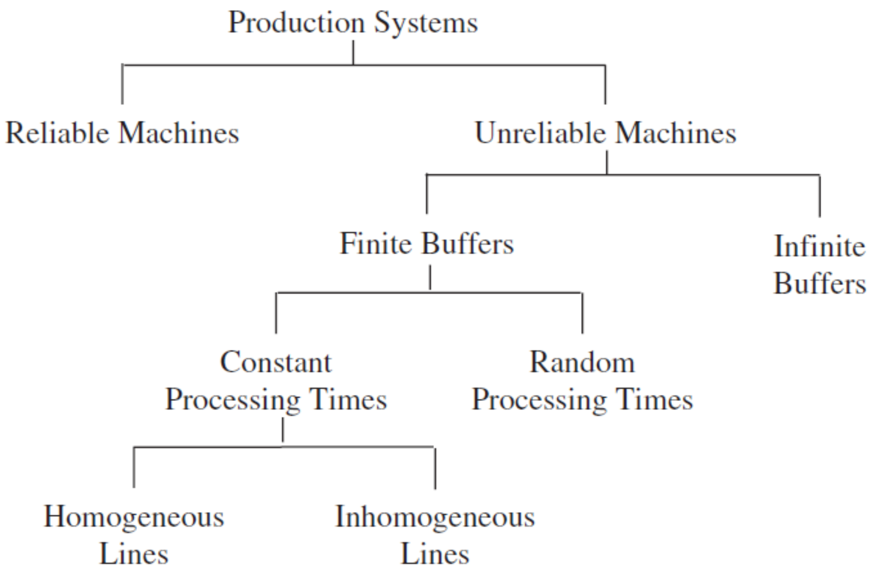



*Figure 2-9 Categorisation of production systems (JINGSHAN LI, 2009)*

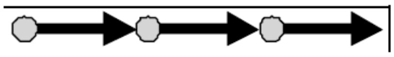
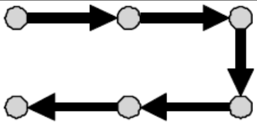
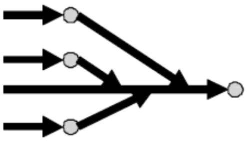
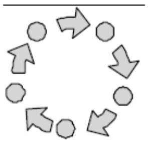
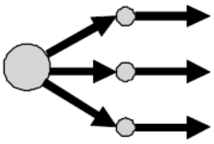
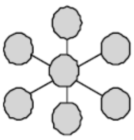
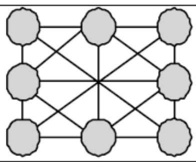
| Basic form | Example |
|---|---|
|  | **Linear**<br>Typical for manufacturing and for assembly work-flows with fixed flow sequence |
|  | **U-shaped**<br>Typical for picking |
|  | **Converging**<br>Typical for assembly with connected pre-assembly stages |
|  | **Ring-shaped**<br>Typical for collection rounds |
|  | **Diverging**<br>Typical for disassembly |
|  | **Star-shaped**<br>Typical for assembly/disassembly |
|  | **Network-shaped**<br>Typical for flexible, frequently-changing workflow sequences |

*Figure 2-10 Common basic forms of material flow in buildings (KETTNER 1984, P. 160)*

### Serial lines

Typical production systems are the serial production lines as it is shown in the Figure 2-15, that shows the representation of this basic flow line implemented in many manufacturing companies (JINGSHAN LI 2009).

### Closed-loop production systems

In a closed-loop system there is a buffer that comes back to another station like in the Figure 2-11 and this can have one or more loops attached to it (JINGSHAN LI 2009).

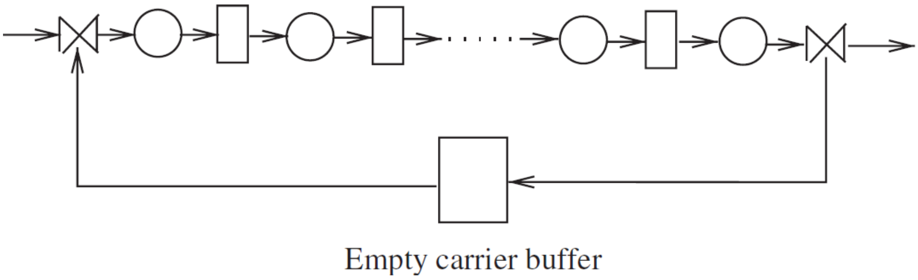



*Figure 2-11 Closed serial production line (JINGSHAN LI 2009)*

**Parallel systems**

One way to get more production capacity is increasing the number of machines in a parallel system like in Figure 2-12 (JINGSHAN LI 2009). This is done because of two reasons. The first one is as mentioned before, to get a better production rate and it happens when some operations are slower than others. The second reason is for getting a greater reliability and this happens when some machines are much less reliable than others. *(DALLERY & GERSHWIN, 1992)*.

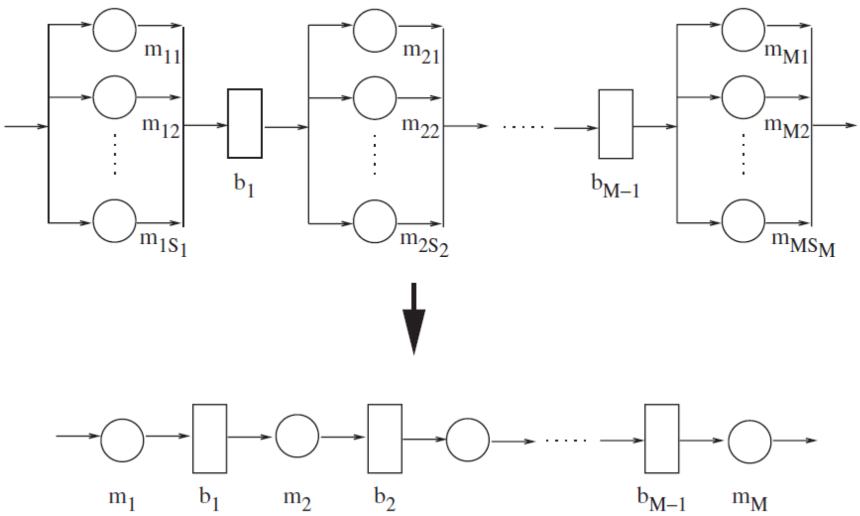



*Figure 2-12 Parallel production systems (JINGSHAN LI 2009)*

### 2.1.6.1 Assembly Process

Assembly is the process of joining parts / components together. It is characteristic for the collection of all the processes used to "combine geometrically-determined elements" (SCHENK ET AL., 2010). In most of the production plants, the assembly process is the last phase of production. During the last years, assembly stations are more automated especially in the automobile industry, therefore there are a lot of robots in the stations. The assembly process takes around 25-40% of the production time. The manufacturing processes and the assembly station will be separated based on the department of the supply industry (SCHENK ET AL., 2010).

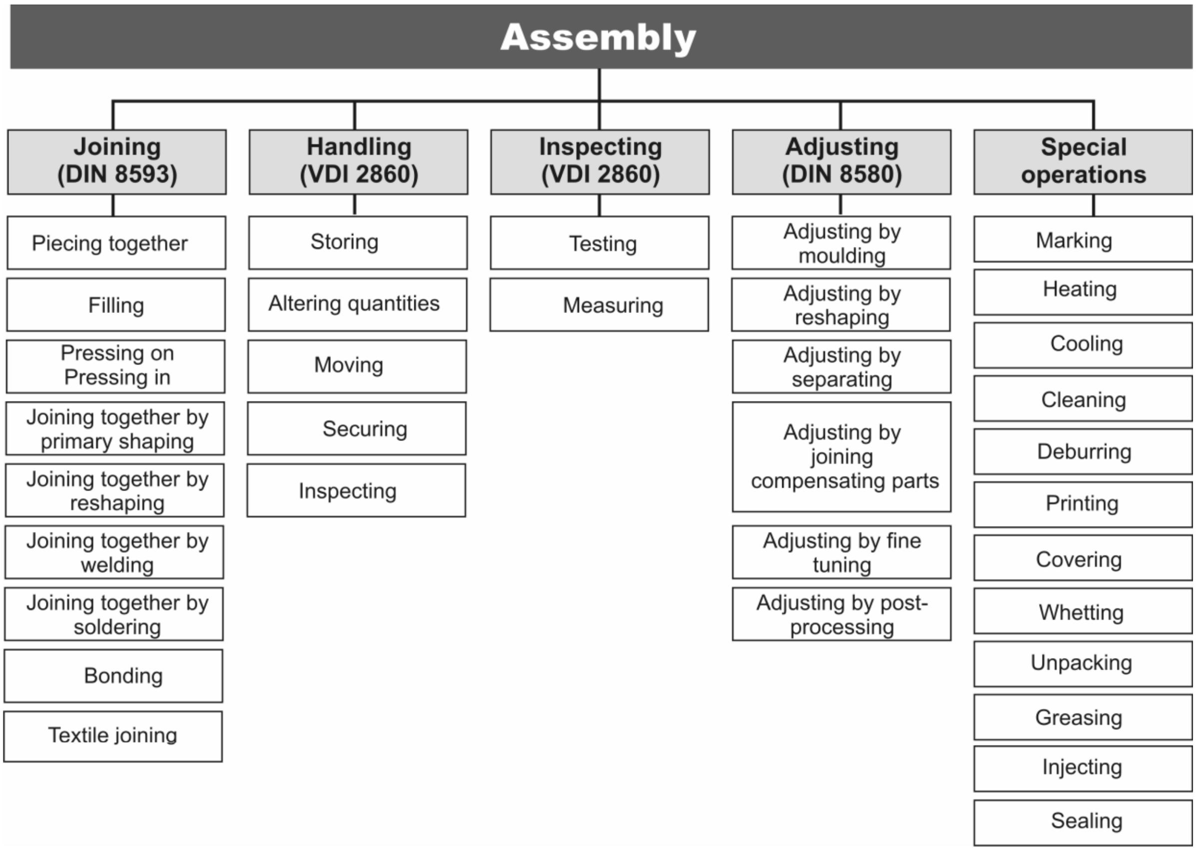



*Figure 2-13 Assembly functions (LOTTER & WIENDAHL, 2006)*

Figure 2-13 mentions the different functions that are interesting to understand them for the reference model.

There are three different types of application of assembly lines:

- Manual assembly lines, where the layout is similar to the manufacturing ones and the effort is split on the different and interconnected workstations. “The field of application here is series production with large product range” (SCHENK ET AL., 2010).
- Assembly lines with robots, which equipment is robots and basically the assembly systems are automatic, fixed and flexible . “The field of application is series production, small and medium-sized products.” (SCHENK ET AL., 2010).
- Hybrid assembly lines with robots are those where people and robots will be working together with spatial segregation. In this case, automatic and manual tasks will be

coordinated. “The field of application is medium and large series for small and medium-sized products” (SCHENK ET AL., 2010).

Regarding the Figure 2-14, it is shown the differentiation between the different assembly applications and the advantages.

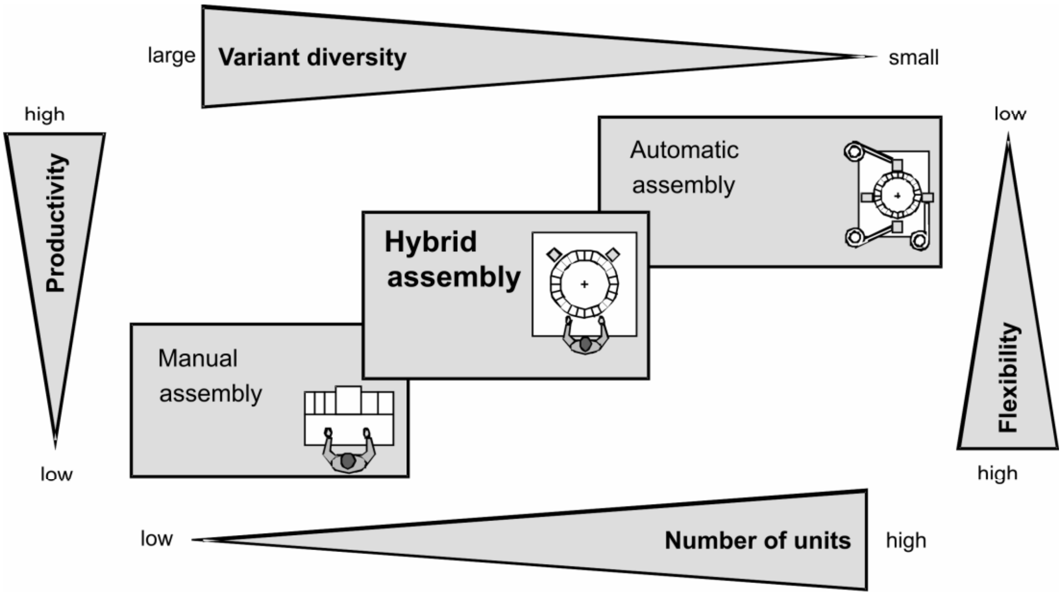



*Figure 2-14 Ranges of application of manual, hybrid and automatic assembly concepts (LOTTER & WIENDAHL 2006, P. 193)*

## 2.1.6.2 Manufacturing Flow

Manufacturing flow is a topic to understand because production systems are based in the flow of different elements. In a manufacturing flow line, also known as production lines, there are two main elements, machines and buffers. On the one hand, **machines** are the work areas where the products are manufactured or assembled and there are storage areas between these machines that are called **buffers** *(DALLERY & GERSHWIN 1992)*. There are two types of buffers, on the one hand there is one for the inventory, therefore unforeseen events will not modify the production lines and they will continue running smoothly. On the other hand, the buffer in the figure is the one between production processes, because there are bottlenecks in some parts of the manufacturing flow and helps to process from the buffering of one machine that will take less takt time (ROBERTSON 2019). The material flows through the different machines and buffers, but these processes will not be the exact same thing because there could be machine breakdowns for example, but all parts will have the same sequence whenever you process the same product. Figure 2-15 shows a five-machine flow line. “Squares represent machines and the circles represent buffers. Machines are numbered from 1 to K, where K is the number of machines in the system and there are K-1 buffers." All the parts have to be processed on all the machines. *(DALLERY & GERSHWIN, 1992)*

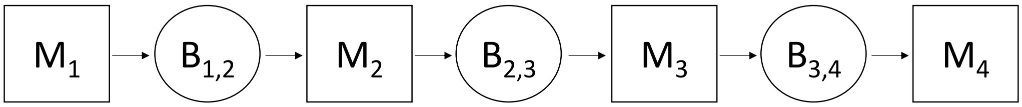



*Figure 2-15 Five Machines Flow Line* (DALLERY & GERSHWIN, 1992)

Here is an overview about the material flow in this flow line, as an example of how the production lines behave. When the machine $M_i$ processes material, it decreases the amount of units in the buffer $B_{i-1,i}$ and the number of units in the buffer $B_{i,i+1}$ gets bigger. In contrast, whenever machine $M_i$. fails or its takt time is really long, and the other machines work normally, the level of buffer $B_{i-1,i}$ gets bigger and the number of units in the buffer $B_{i,i+1}$ are reduced. If this continues this way, buffer $B_{i,i+1}$ could be empty and buffer $B_{i-1,i}$ could be full, and this is not good for the production line. Because of these delays or different processing times, buffers exist and become empty or full. With all the machines synchronized, without breakdowns and with the same processing times, buffers would not be useful. But this is an ideal system and therefore it is important the planning process of the production line, to try to optimize the manufacturing flow line *(DALLERY & GERSHWIN, 1992).*

### Flow systems

Logistics and production and all kind of activities related with the adding value processes need to be planned together with the goal of optimizing the flow and connected to each other through a continuous flow (KLUG 2010, PP. 257-258). In order to achieve this continuous flow and optimized flow system, the product itself must be the focus of all the different process, despite the limitation between different departments and areas, and taking care of the continuous flow of the product (WOMACK & JONES 2003, PP. 51-52). Advantages of this continuous flow is decreasing and avoiding waste between the production steps (DURCHHOLZ 2013, P. 48). In addition, the different reasons of stopping the continuous flow should be considered like machine breakdowns or product defects and try to avoid them, for example with a good prevention of maintenance (WOMACK & JONES 2003, PP. 51-52). With the help of further lean principles such as Single-Minute Exchange of Dies (SMED) is possible to improve the constant flow, like reducing set up and changeover times to a minimum (KLUG 2010, P. 258).

For the running of a manufacturing facility, different process elements like material, information and energy and their connections between each other need to be planned and implemented. Due to the process functions are also known as flow functions, there are these three main flows, which are material, information and energy flow and it is as relevant the object as their related systems and facilities. Due to the interconnectivity between each other, one change in a flow can have a big effect on the production facility. As it was mentioned before, flexible processes provide better flow systems adaptability and competitiveness (SCHENK ET AL., 2010).

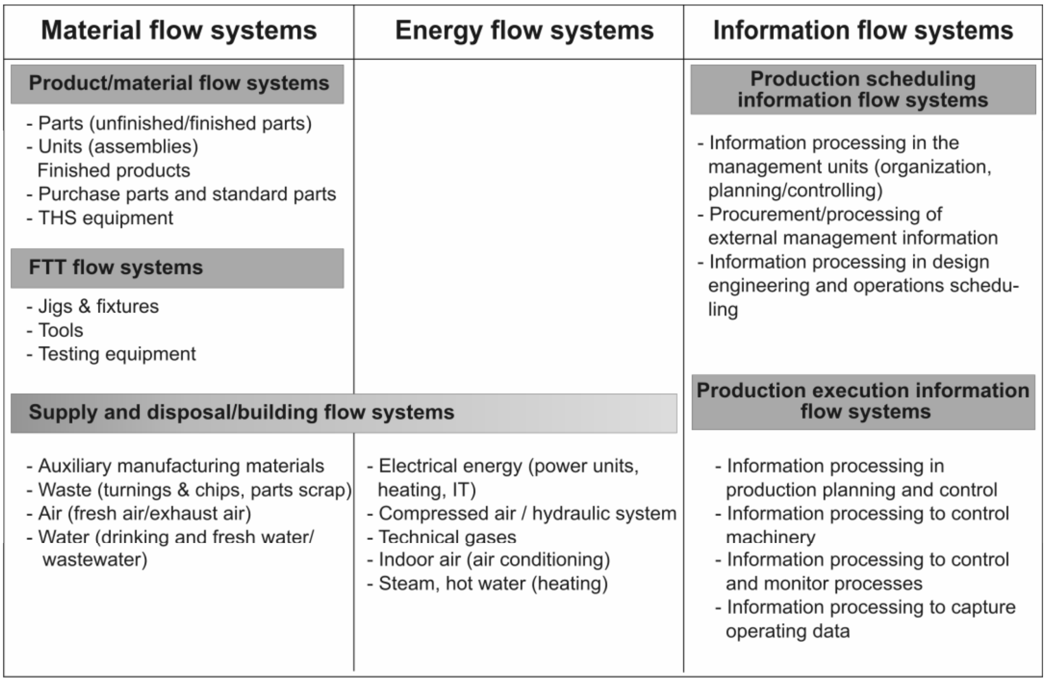



*Figure 2-16 Material, Energy and Information flow systems examples (SCHENK ET AL., 2010).*

In the Figure 2-16, the three different flows and some elements are shown to understand them. Here there is a small introduction to these concepts which will be important for the model later on:

**Material flow**: the planning of how is the movement from unfinished parts till the end with the finished products.

**Energy flow**: during all the processes, there is a need of energy flow, therefore different energy flows in the three different forms like the power equipment for electricity, water supply or compressed air could be supplied.

**Information flow**: information is everywhere and for managing a production facility it is required to share data with the different IT equipment to plan and execute production. Information is important in all the areas like planning, scheduling, coordination, communication and technical control of plants.

There are more additional flows and these two will be mentioned shortly as well:

**Personnel (work) flow**: nowadays there are already robots in the production facilities but an important and basic aspect is the workforce flow, because all the processes need interaction with personnel and also for controlling it.

**Capital and cost (value) flow**: adding value process is the main goal of the manufacturing facility and there is a continuous flow during the processes related to the equipment or resources needed and the product value (SCHENK ET AL., 2010).

## 2.2 Intern Logistics

Logistics procedures in the manufacturing industry are gaining in significance. Not only because of globalization, but also because of increased demand for extremely individual products with shortened life cycles. According to the definition of lean management, logistics can no longer be regarded as waste, but must be treated as another significant element of the entire manufacturing scheme because all the processes are interconnected. (BRAUN 2018)

Transport, handling and storage processes (THS processes) are the main core of logistics. On the one side, focusing on the transportation of goods/workpieces between the different points of destination by conveying and handling (transferring, un-/ loading) and on the other side, keeping the materials and resources in the storage area for the inventory management and the production system. (SCHENK ET AL., 2010)

On the next paragraphs, there will be some definitions about logistics:

Regarding these authors (ARNOLD ET AL. 2008, P. 3, GUDEHUS 2012, PP. 6-9) **logistics processes** cover the transport and storage processes with the handling, loading and commissioning tasks necessary for these procedures always with the objective of demand-oriented supply.

In the case of **logistics objects**, they are including all the products, services and materials which are supplied to some destination or goal (ARNOLD ET AL. 2008, P. 3, GUDEHUS 2012, PP. 6-9).

The resources required to perform efficiently the different logistic processes are the **logistics system** and is modelled as a network. This network is about nodes connected through lines representing the routes of transport. In this nodes are represented for example the storage facilities (ARNOLD ET AL. 2008, P. 3, GUDEHUS 2012, PP. 6-9). According to its design, the real movement of logistics products in that network is therefore called either material or information flow (ARNOLD ET AL. 2008, PP. 4-7).

In addition to these definitions, logistics includes all the duties engaged in supplying a certain item to the assembly station, such as planning, controlling and tracking and managing the flow systems like information, material, personnel and energy flows within the company concerned. (PFOHL 2010, P. 12), (SCHRÖDER 2017, P. 10). In this definition, logistics is in charge of controlling and organizing the networks and flows to achieve economic, ecological and social goals (DELFMANN ET AL. 2011).

As it was explained before, the topic about SCM is really connected to logistics and this is because of the importance to understand all the coordination of the entire value chain, from product development to aftersales (ARNOLD ET AL. 2008, P. 21).

Logistics planning's primary objective is to implement an effective network driven by the material flow and to ensure a stable value chain. Efficacy is about all the processes related with material flow, like the product (quantity and type) arrives to the destination in time (PFOHL 2010, P. 12). Logistics suppose high costs to the company because of the amount of objects that need to be moved and stored (SCHENK ET AL 2010). Regarding this logistics planning, it is important to take into account the cost in all the processes. If you are not efficient, a decision of reducing transportation costs, because of the high cost of supplying the raw materials, will influence in the inventory of the company, reducing the amount of units to manufacture (PFOHL 2010, PP. 29-30).

Logistics is interconnected with all the processes inside a company production. Through the transportation of materials with the necessary resources (like a moving fork lift) and the inventory from the storage, logistics is a main topic for the value flows. In Figure 2-17 is shown the central position of logistics in the company management (SCHENK ET AL 2010).

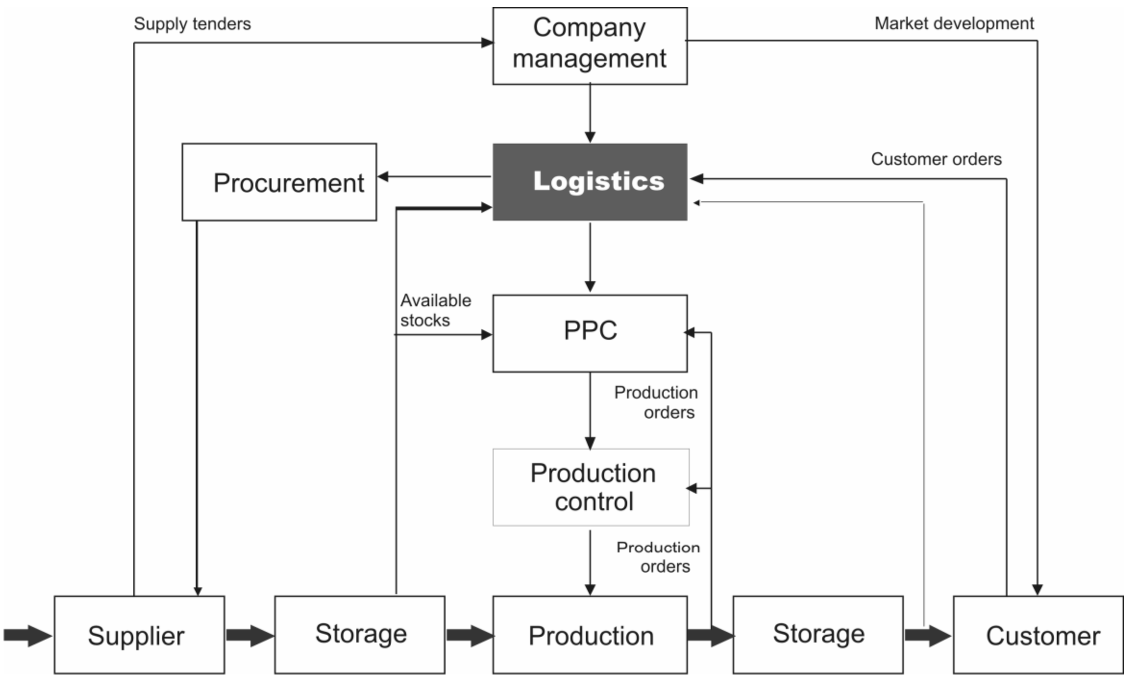



*Figure 2-17 Central position of logistics in the enterprise between markets and production (KRAMPE 2007, P. 141)*

### 2.2.1 Transportation

Transportation is one of the main elements of logistics. In this case, it is focused in the internal transportation because the reference model is based only in the manufacturing part of a company and consequently, paying attention to the transportation and material movement between the different areas of the factory. Important facts to take into account for the transportation planning in a factory would be: (SCHENK ET AL 2010).

• type and quantity of materials for transporting,

• the type and amount of transport resources like a fork lift,

• staging and disposal areas,

• best transport routes for an efficient procedure,

• the type, size and principle location of buffers,

• the skills level and number of workers and

• the type and scope of all tools and devices

After seeing all these elements for transport, (SCHENK ET AL 2010) explains a quick overview about how are the steps to select the best means of transport for the logistics processes. These steps are a good way to identify the transportation system in a factory.

1. Find out which are the tasks about the transport based on the type of product, quantity and weight, time, special regulations for the safety of the factory plant, etc..
2. In this step, the basic principle of continuous or discontinuous movement is selected. Depending on that and on the level of the movement through the factory, different transport element will be chosen. On the one hand, there are under-floor transport like conveyor belts, floor-based transport like fork lifts and overhead transport like cranes. Between these three levels, alternating floor transports are required for example elevators.
   This step has a big effect on the layout and structure of the building and therefore, all these planning processes need to be planned before starting the building of the infrastructure. Depending on the transportation, the layout will be different, having in mind aspects like the heights of the building, the floor spaces…
3. Once the transport level is chosen, it is relevant to calculate the capacity of the transportation.
4. Choose the most efficient paths and areas for the crane track installation.
5. Last step is to calculate the maximum loads of the transportation equipment and infrastructure like floor loads.

| Data describing transport task | Content examples |
|---|---|
| Commodity to be conveyed | Type, number, mass, dimensions, logistical characteristics |
| Transport time | Overall transport time and individual times for pick-up, travelling, braking and delivery |
| Frequency of transport | Frequency per type of transport |
| Transport utilities | Type, characteristics, dimensions, costs |
| Means of transport | Type, dimensions, carrying capacity, speed, costs |
| Transport route | Length, type, nature |

*Figure 2-18 Data describing the transport task and solution (SCHENK ET AL 2010).*

## 2.2.2 Handling / Picking

Handling and picking processes are also a main element of logistics and come before the storage processes planning, for being more effective and having lower cost solutions. These processes are essential for every element in the factory, from the main product and subassemblies, to tools, required equipment, special jigs and fixtures and even packaged goods that need to be provided or supplied (SCHENK ET AL 2010).

For achieving these tasks, it is necessary to being directly related with the transport resources, to help the workers in the execution of the handling and picking. In many cases picking vehicles are utilized to assist in efficient execution of the picking process and support the workers. Just to introduce some elements of transportation that will be mentioned again in the reference model. There are picking vehicles like “order picking trolleys, order picking stacker, order picking trucks and storage and retrieval units for high rack warehouses”. There are also automatic robots or known also as Autonomous Guided Vehicles (AGVs). It is necessary to move these items to a picking area and therefore it is needed systems like conveying, sorting and transport. To link all picking areas into a single unit, transport, conveying and sorting systems are required. These systems are in charge of the distribution, providing empty containers and removal (SCHENK ET AL 2010).

Here is classified the picking time in different categories and a good way of understanding the picking processes: (SCHENK ET AL 2010).

• basic time: organizational tasks, collecting containers, distribution

• travel time: the time of planning the route for the removal locations

• grab time: removal, collection, conveying, distribution

• dead time: searching, counting, checking, labelling

Some different terms to understand better this topics would be the **picking quality**, that is the percentage of goods well picked and on the other hand, the **picking or handling output** would be the total number of units picked in a certain period (SCHENK ET AL 2010).

### 2.2.3 Storage

Storage is another key element of logistics and is any scheduled and organized deposit of parts or goods within the material flow, according to VDI 2411. Consequently, a storage defines an area, space or unit. When storage is mentioned, the main definition would be related with larger stores where you store all the goods and the supplied materials but in production there are also the buffer stocks and these two areas will be designed and dimensioned separately. In the buffer stocks, there are different types for example the dynamic buffers like a circular conveyor or an stationary one, like magazines. In the storage systems there are different categories of activities that are subdivided in the following: (SCHENK ET AL 2010).

• Preparation in storage (preservation, packaging, palletizing, labelling)

• Transfer to bin (charging units, transport to storage)

• Storing and controlling (bridging the time of storage, potentially maintenance, inventory control, relocation)

• Transfer from bin (collection, consolidation, packaging, labelling)

• Post-processing in-storage (unpacking, repacking or packaging, cleaning, removal of dust)

After describing the activities of the storage systems, it is relevant to mention the storage facility functions. Therefore the functions of a warehouse would be keeping the material supply, with the ability to move it easily between internal and external facilities and customers, balancing the quantity of it based on the production demand, with the preparation and sorting the materials for the production orders and speculating on different aspects from the future like price fluctuations, shortages, seasonality and strikes (BICHLER 1997, P. 155)

Failure to plan or organize wrong the storage facilities can lead to severe malfunctions and bottlenecks. Warehouses have different areas and special facilities like ramps, doors, staging areas and other functional areas (SCHENK ET AL 2010).

Here in Figure 2-19 there are some simple floor storage examples, that will be mentioned later on in the reference model.

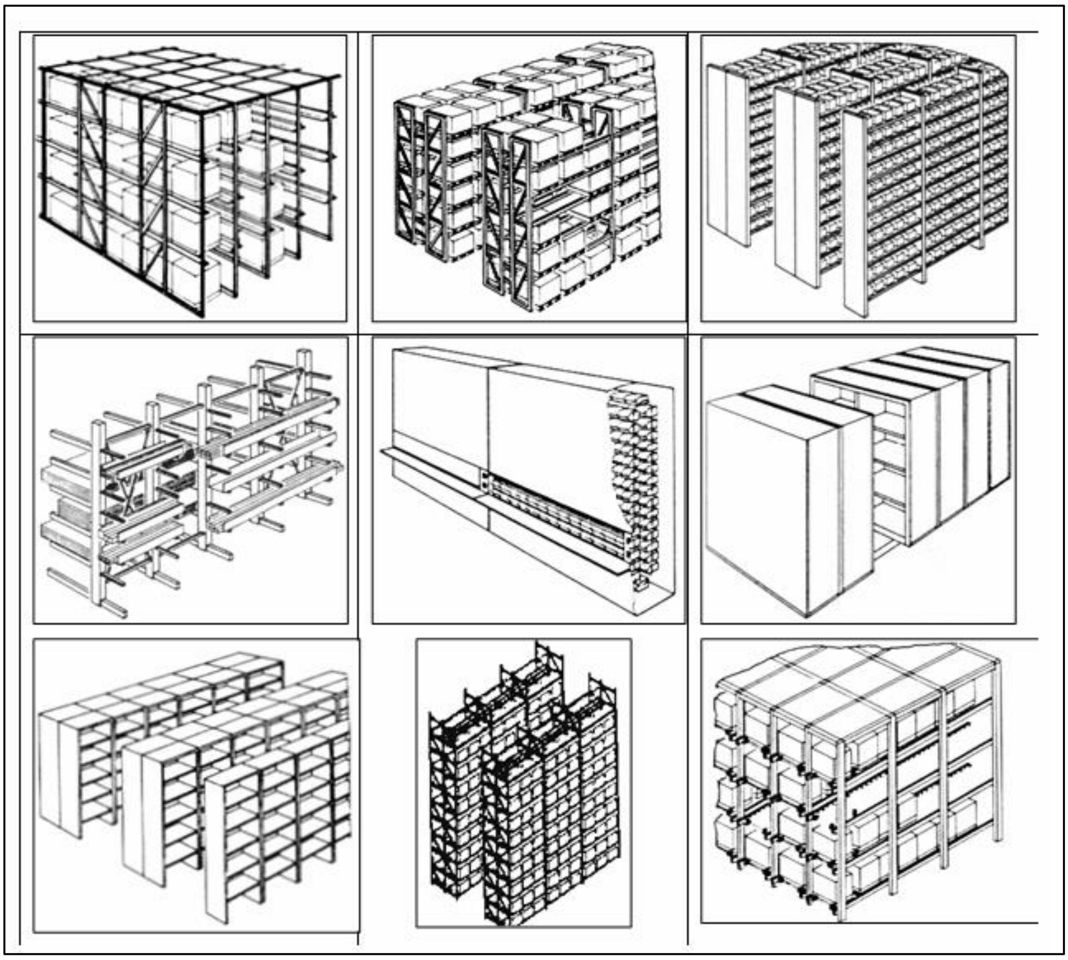


*Figure 2-19 Storage facilities (JÜNEMANN 1989, P. 153)*

### 2.2.3.1 Inventory

Inside the storage, it would be the inventory an important term to mention, because inventory is the usage of the storage systems somehow. For most of the companies of the manufacturing industry, controlling and maintaining the inventory is a vital problem to the manufacturing processes. This is a relevant topic because every day production managers need to deal with this depending on the number of units to supply to the customer, because if you do not take into account this, it would be difficult to satisfy always the customer demands. Basically the inventory topic is a problem of balancing in the best and most efficient way to comply with the needs of the customers, and having the items available whenever they need them. It is important to think about this balance because inventory costs are high and the planning and control about the quality and quantity is required (FRANCIS 2005).

During the last years and the globalization of the industry, inventory management is a relevant topic for those companies selling globally and it is required holding goods for achieving a good customer service. Managers need to think about the planning of how many warehouses are needed and which quantity on them, for ensuring the customer service in a high level (FRANCIS 2005).

Inventory has been described in different ways but to understand the meaning, there are mentioned these definitions. From the definition of (BALLOU 2004) “Inventories are stockpiles of raw materials, suppliers, components, work in progress, and finished goods that appear at numerous points throughout a firm’s production and logistics channel” to the definition from (CHASE, JACOBS & AQUILANO 2004), inventory shall be the stock of any item or resource used by a company. The function of an inventory system is to control and balance the inventory levels and determine what levels should be kept, deciding when the inventory should receive more supplies and how and when the execution orders should be.

## 2.3 Maintenance

Maintenance covers the production system in a factory during the whole process. The ever-increasing pressure for productivity and pricing strategies to compete is forcing firms to implement efficient maintenance schemes. A clear communication between the individual interfaces, manufacturing, IT and maintenance is needed in order to achieve such modifications (KÜHNS 2018).

By law, companies are needed to comply with laws on occupational health and safety and the environment, which also apply to plant management, therefore the element of regulation and policies will be mentioned in the reference model. Maintenance contributes significantly to legal security, occupational safety and environmental protection through resource optimization and occupational safety measures in manufacturing and, in the long term, to the future of the business (SCHRÖDER 2010, P. 1).

Maintenance is defined as "all measures for the preservation and restoration of the target condition as well as for the determination and assessment of the actual condition of observation units". An observation unit can be any component, device, subsystem, functional unit, equipment or system that can be considered on its own (DIN EN 13306 & DIN 31051). The main maintenance goal is to delay this wear and tear and to prevent the corresponding observation unit from failing. Its scheduling is also crucial in relation to the maintenance duties to be conducted.

DIN 31051 divides maintenance into four basic measures: inspection, maintenance, repair and improvement. In the thesis was divided in three basics as it is shown in the reference model and it will be explained later.

The **inspection** involves all actions taken to determine and evaluate the real state of the technical facilities. The inspection also identifies the causes of wear and tear and draws the conclusions necessary for future use.

**Maintenance** is in charge of the periodical tasks for preventing these breakdowns and its duties would include lubrication, cleaning and adjustment of the observation units.

**Repair** is all work to restore a observation unit to working order, with the exception of improvements.

**Improvement** measures are a mixture of all technical and administrative measures as well as measures to enhance an observation unit's functional efficiency without altering its function for the best of the manufacturing plant in the future.

The objective of staff maintenance policies is to improve maintenance effectiveness by qualifying the staff responsible for maintenance duties and standardizing the preparation and execution of a maintenance order (BLOSS 1995, P. 17)

# 3 Modelling

The models are like some mathematical models describing the key concepts for understanding, compromises between reality fidelity and tractability. Engineers use modelling to do simplifications of reality and therefore, the modelling of production systems will be done. Modelling is done for explaining a theorem for example, because it is more complex to compare with reality (DALLERY & GERSHWIN 1992, P.5).

For understanding the modelling of the production system, a word to develop more would be complex system that is “a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and / or change” (MAGEE & DE WECK 2004).

Modelling is the process to define, explain and design real systems in a simplified way (GAJEWSKI 2004, P. 7). Another definition about the term model is defined by (VDI 3633): "A model is a simplified reproduction of a planned or real existing system with its processes in another conceptual or objective system. With regard to the properties relevant to the investigation, it differs from the "model" only within a tolerance range dependent on the objective of the investigation”. Regarding the Figure 3-1, models are characterized by three characteristics: the mapping characteristic, the reduction characteristic and the pragmatic feature (STACHOWIAK 1973, P. 131).

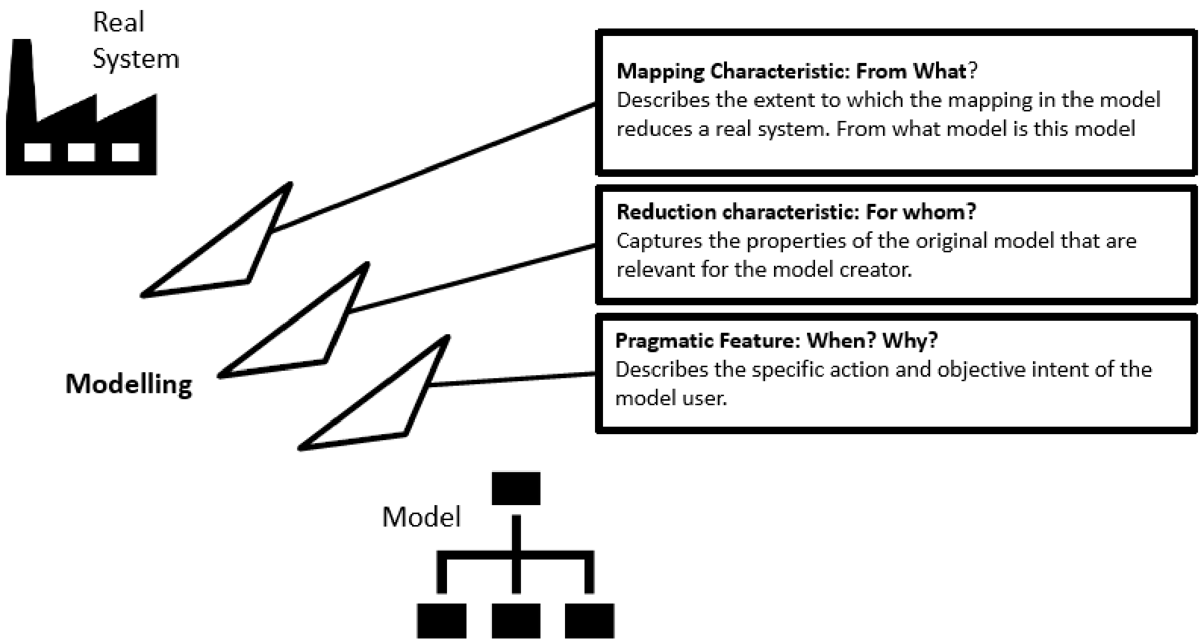



*Figure 3-1 Characteristics of a model (NEUHAUSEN 2002, P.53)*

## 3.1 Why Modelling?

Due to the increase of market dynamics, product individualization, shorter product lifecycles and greater frequency of innovation, the environment is turbulent (ABELE ET AL 2006), and companies need to be flexible and have changeable manufacturing systems (WIENDAHL ET AL 2007).

Structural modelling is a strong analytical and assessment method. The application of structural modelling to a production system increases the possibility of identifying and analysing e.g. scheme features and future improvements as single systems (KOCH ET AL 2014)

The purpose of this modelling is focused in a current factory for example, and the model will help to create an specific model for this factory and at the same time identifying the elements that it has or not. The planning process itself would not be the focus but the actual manufacturing processes are the key elements. All the elements of the factory are important to gather and how they are connected between them (BAUER 2019).

In order to support the planning, analysis, visualization or optimization of the corresponding manufacturing system, countless software products, modelling languages and techniques have been created (PLEHN, 2015).This thesis is an effort to fill this gap for the manufacturing industry and helping the companies with these problems of identification and future changes.

### 3.1.1 Requirements of factory system modelling

For achieving the modelling purpose, the requirements must be stipulated first to characterize and guide the scope of the modelling and to guarantee that the resulting design assistance is built in accordance with its expected purpose. The requirements of the reference model will be explained in chapter 5. The model needs to have an intuitively and understandable visual representation, however with an industrial application perspective to provide an attractive tool (PLEHN, 2015). Therefore the metamodel is an useful tool to work with the current complex factory systems because it can be adapted and expanded by the users, and this is a relevant aspect for our production system model. Furthermore, the modelling approach needs to enable an automated quantitative analysis of factory systems.

## 3.2 Different Modelling Methods

In this section will be explained in what are based the different modelling methods and there will be an introduction of some of them. For modelling a common software or system design process, there will be needed different backgrounds, because of the complexity with the interconnections between all the elements like the information flow and other variables. (STEWARD, 1981; WANG ET AL., 2014).

A way of modelling is starting with a classification of elements in different categories for example domains in the extended manufacturing system (ExMS). The elements can be assign to each domain and in this case there are "product", "manufacturing process", "manufacturing resource", "cyclic influencing factors" and the "continuous reconfiguration planning (CRP)" , which these domains had a big influence in the reference model of the thesis. This is because these domains are interrelated and they are based on different elements (nodes) interconnected between them (edges). To understand this in this case, "manufacturing processes" requires "manufacturing resources". These relations between elements are visualized in different ways of modelling, for example with matrix or graph representations like in the structural complexity management (StCM) (KOCH ET AL, 2014).

In the matrix representation modelling, there will be mentioned three types of them. The Design Structure Matrices (DSM) is a subset of a single domain, e.g. the relationships between distinct production procedures. This is a N x N matrix that maps the relationships between the set of N system components "highlighting the architecture of a system" (EPPINGER AND BROWNING 2012). It is implemented in a multitude of fields due to the simplicity and flexibility of its idea. DSM is also used in project management to enhance the planning, implementation and management of complicated projects by concentrating on information flow optimisation (STEWARD, 1981; GUNAWAN, 2012). The mapping of two distinct domains is represented by a Domain Mapping Matrices (DMM), like in the example before for ExMS, relations between manufacturing processes and resources domains (DANILOVIC & BROWNING 2007). A Multiple Domain Matrices (MDM), another matrix model, involves at least two domains and DSMs and DMMs associated subsets (LINDEMANN ET AL 2009). These matrix-based representations of a structure could be also visualized in graphs representations to be analysed in a different way.

Other modelling methods to mention would be the Systems Modelling Language (SysML) that is inside the Unified Modelling Language (UML), which uses graphic notation to create visual models of software systems in the area of Systems Engineering (PLEHN, 2017). SysML is a standardized, graphical modelling language capable of representing systems and their components' specifications, behaviour, structure and characteristic (VALILAI AND HOUSHMAND, 2009; DEBBABI ET AL., 2010) and Object Process Methodology (OPM) that uses a decreased set of construction blocks and only one unified diagram type to reduce the effort required to generate, synchronize and maintain a full range of system and function modelling diagrams (DORI 2002; DE WECK ET AL., 2011).

As an example of the procedure of a modelling method, in the StCM, there are four steps to create a model. Starting with the visualization of the metamodel and its relations so it would be the "system definition" phase. After that, more information in detail about the edges to develop the DSM and DMM subsets "deduction dependencies". Then the "structure analysis" phase where the identification and analysis of the model is done and finally the "practical application", that would be the validation of the model and improve it (LINDEMANN ET AL 2009).

In the Figure 3-2 is shown the MDM metamodel with the different five domains and the edges in the matrix representation of the ExMS as an example of a model.

| | **Cyclic influen-cing factors** | **Product** | **CRP** | **Manufacturing resource** | **Manufacturing process** |
|---|---|---|---|---|---|
| **Cyclic influen-cing factors** | influence | influence | are considered | influence | influence |
| **Product** | | influences | considered in | influences | influences |
| **CRP** | | | follows | analyzes | designs |
| **Manufacturing resource** | | | | are connected | |
| **Manufacturing process** | | | | is required for | enables |

*Figure 3-2 Metamodel of the extended manufacturing system (ExMS) (KOCH ET AL 2014)*

In modelling of manufacturing systems, there is a model that distinguishes between different layers of a factory system that could be interesting to mention for seeing the different levels established (WIENDAHL ET AL. 2007). "**Factory systems** comprise the spatial arrangement, relations, and properties of technology, personnel, and infrastructure in a differentiable sub-section of a manufacturing plant" (PLEHN, 2015). In the Figure 3-3 is shown the distinction between the different layer models divided in network, factory, segment line, station and technology level.

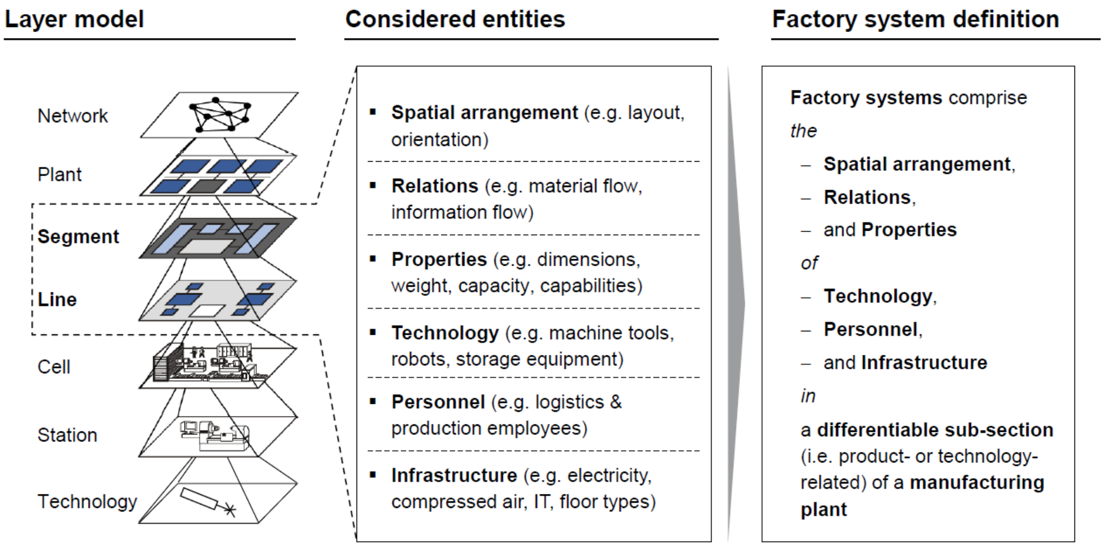



*Figure 3-3 Layer model of production systems and factory system definition (PLEHN, 2015)*

## 3.2.1 Metamodel

When an abstraction procedure is done to a model itself, then a **metamodel** appears which expresses certain properties of a model (JEUSFELD, 2009; PAIGE ET AL., 2014). The definition of a model is "a formal description of phenomena of interest, constructed for a specific purpose, and amenable to manipulation by automated tools" (PAIGE ET AL 2014). As it was explained before, models simplify and describe properties of the real world (SPRINKLE ET AL 2010). Therefore, some simple definitions of metamodel are "a metamodel is a model that consists of statements about a model" (PAIGE ET AL 2014), "a metamodel makes statements about what can be expressed in the valid models of a certain modelling language" (SEIDEWITZ, 2003). "A metamodel is a description of the abstract syntax of a language, capturing its concepts and relationships, using modelling infrastructure" (PAIGE ET AL 2014).

The primary benefits of creating metamodels are that they document and support language evolution over time, they allow flexibility in designing and encourage the development of well-formed designs, support model transformation and formal model characteristics checking. (PAIGE ET AL 2014).

In Figure 3-4 and Figure 3-5 are represented the metamodel for nodes (elements) and edges (connections) of a manufacturing system. The nodes metamodel is divided in five layers and characterized by levels with the highest level on the top although is not necessary to have five layers for each branch.

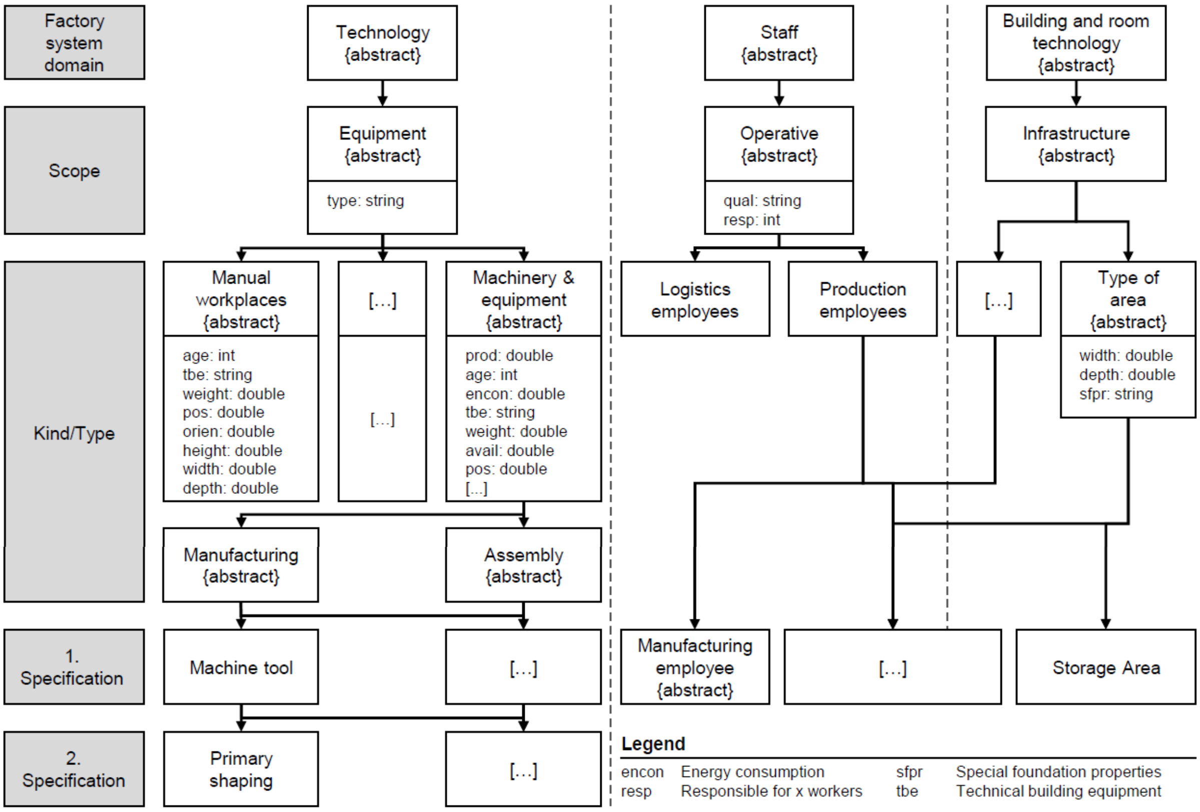



*Figure 3-4 Developed nodes metamodel (PLEHN 2015)*

The relationship between different elements is done with edges and this model has only three layers. In this case, the interconnection between elements is done with five types of flows with same structure like in the nodes metamodel, with the highest level on the top.

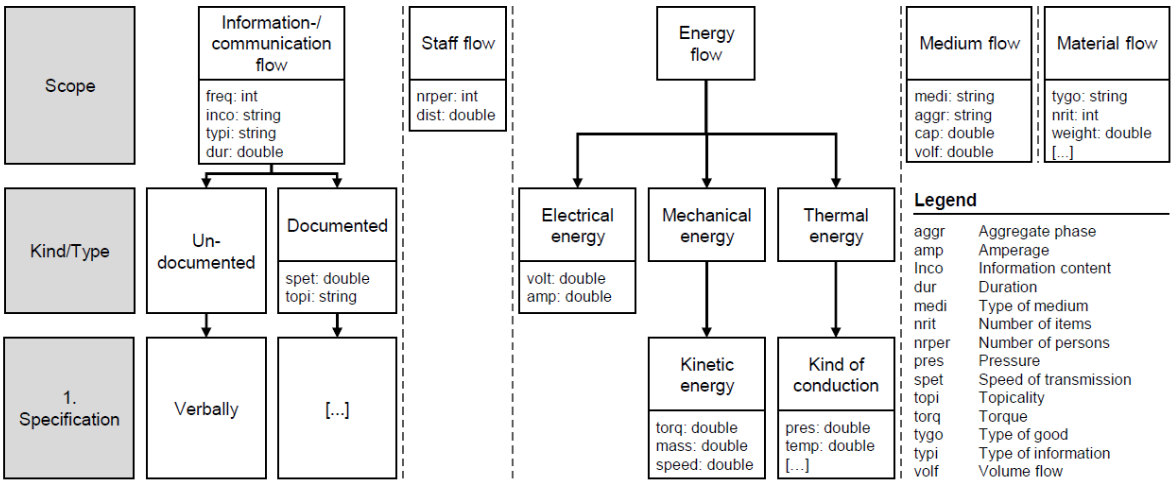



*Figure 3-5 Developed edges metamodel (PLEHN 2015)*

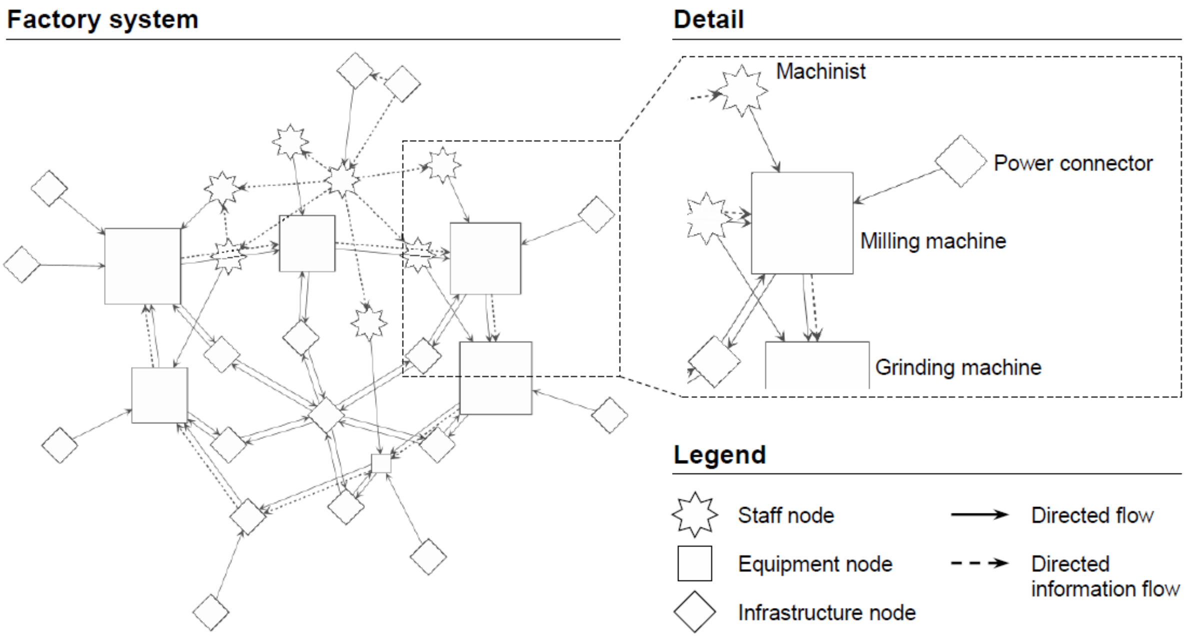



*Figure 3-6 Example of a graph model for a compressor shaft production (MÜLLER AND ACKERMANN 2013)*

This example simplified to only the model of a compressor shaft production in Figure 3-6 visualize the nodes and the edges with the different flows. The model represents in an abstract way all the structural properties of the production system.

## 3.2.2 Product, Process and Resource

For producing the demanded **product** from the customers (quantity of product, dimensions), these products require some **processes** to be manufactured with the **resources** of the facility to produce them (equipment, tools) where workers control and supervise everything (SCHENK ET AL 2010).

As it was mentioned before in the extended manufacturing system, the five domains for a production system would be product, manufacturing process, manufacturing resource, cyclic influencing factor and the CRP processes (KOCH ET AL 2014). In this section, these elements will be explained however the main elements for the model are **product, process and resource**. In any case, the other elements could have been taken into account, nevertheless they were not mentioned because they are not in the actual manufacturing process, they are more inside the planning process (BAUER 2019). Product, Process and Resource (PPR) are the key elements of engineering domain in any automotive industry (RAZA & HARRISON 2011).

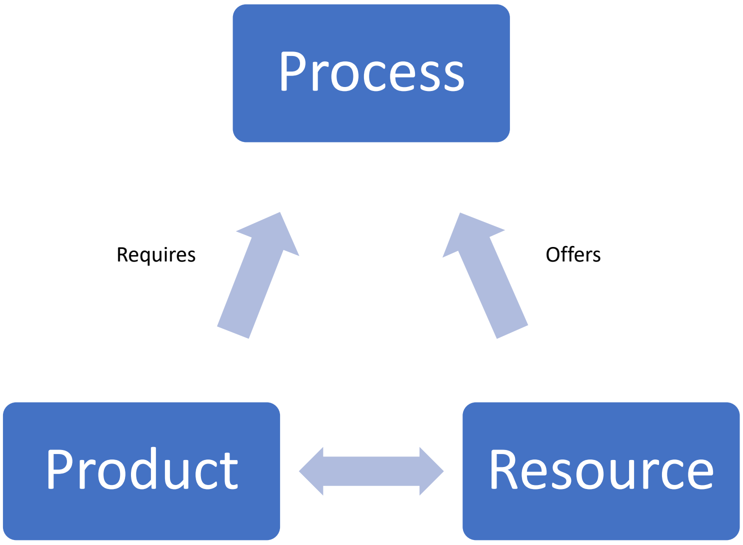



*Figure 3-7 Product Process Resource representation (RAZA & HARRISON 2011)*

The elements are divided into two categories, tangible and non-tangible elements. Inside physically tangible elements are manufacturing resource and product and on the other side, non-tangible elements are manufacturing process, cyclic influencing factors and CRP process. (KOCH ET AL 2014)

These last two concepts are defined here:

- Cyclic influencing factors: influences on elements of the manufacturing system causing changes for e. g. manufacturing resources (product life cycle, technical changes, production technology life cycles) (ZÄH ET AL 2010)
- CRP process: continuous planning process for reconfigurations of manufacturing resources (KOCH ET AL 2014).

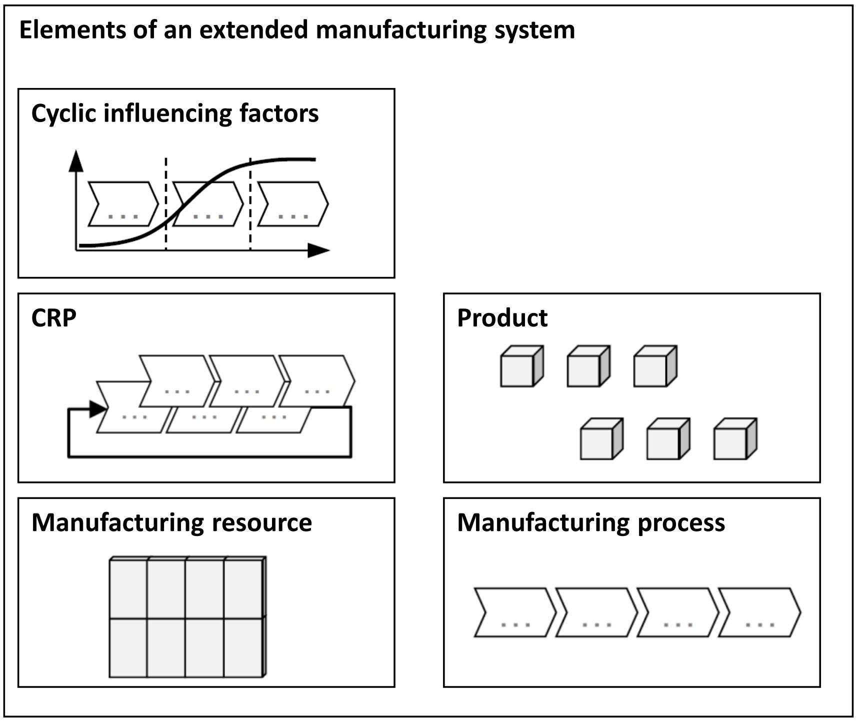



*Figure 3-8 Elements of an extended manufacturing system (KOCH ET AL 2014)*

In this section the main concepts of PPR will be explained in more detail:

**Product**

The goods manufactured with the resources, containing elements (e.g. subassemblies, modules) and possessing attributes (e.g. geometry, size) (KOCH ET AL 2014). When the term product is mentioned is not just the finished goods but every kind of physical object that constitute a part of the product. There are different elements in the Product domain, here there are the "Product, Subassembly, Product family, Component or Attachment". The same product or part can be different concepts for different companies because that product can be the finished good of the company but the subassembly of another manufacturing company (AGYAPONG-KODUA, HARASZKÓ & NÉMETH 2014).

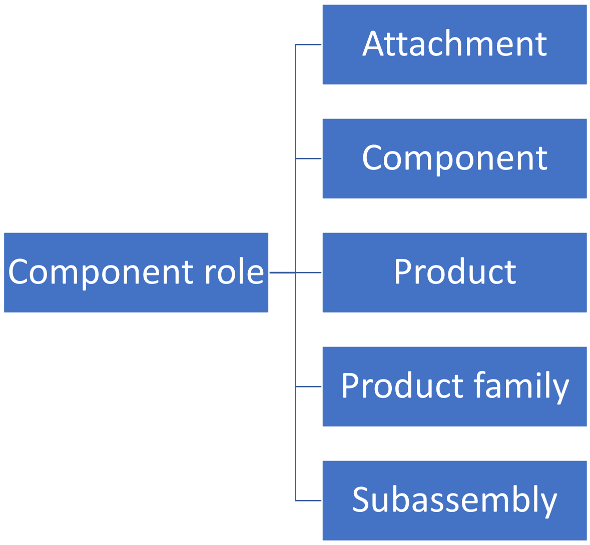



Figure 3-9 Product domain classification (AGYAPONG-KODUA, HARASZKÓ & NÉMETH 2014)

- A product is a material, piece part, or assembly produced for sell to a customer or business.
- A subassembly is an assembly intended to be used inside another assembly as a physical interlinked item. Usually, a group of subassemblies could be the structure or components of a product.
- Components are assembly objects from the point of view of the assembly system. Either they can be individual monolithic machined components or their own complicated subassemblies that come from a source outside the assembly system in question.
- An attachment is a piece of material used to join together two components. Examples of attachments are: rivets, screws, paste solder, adhesives, etc.

(AGYAPONG-KODUA, HARASZKÓ & NÉMETH 2014)

**Process**

Process for creating a product using manufacturing resources (CHRYSSOLOURIS 2006). The bridge between the product and the resources is called ‘process’ and it is the one that manufactures the product through a sequence of processes. Processes can be also the complex activities of a group of several lower activities like tasks, operations, actions…(AGYAPONG-KODUA, HARASZKÓ & NÉMETH 2014).

Typical elements of the process domain in our model could be for example joining or cutting because they are actual processes but not too detail for each company.

**Resource**

All the resources like machines, devices and equipment, that were used for the creation of goods in the company (VDI 1978).

(AGYAPONG-KODUA, HARASZKÓ & NÉMETH 2014) divides the resources in three concepts and these would be the system configuration layout, the equipment type and the workforce. The system configuration layout concept is related with the layout type, the influence on the manufacturing system and on the infrastructure. The equipment is the necessary devices, tools, machines, etc.. to offer the possibility of doing the product. The human resource concept is about all the knowledge of the workers necessary for the process and furthermore the tasks and control that they need to do during all the processes.

In the reference model of the thesis, the resource concept is related with all material, tangible or non-tangible that provides or helps to the manufacturing process of the products. In this case, an example of tangible resource could be a tool like a screwdriver however in the non-tangible element, an example could be the knowledge about a new tool, like the analysis of big data in a computer can provide you the solution to do the process to produce or control an assembly.

**PPR elements**

The elements of a system of production according to (WESTKÄMPER & LÖFFLER 2016) are all transforming organizational and technical processes, people and plants.

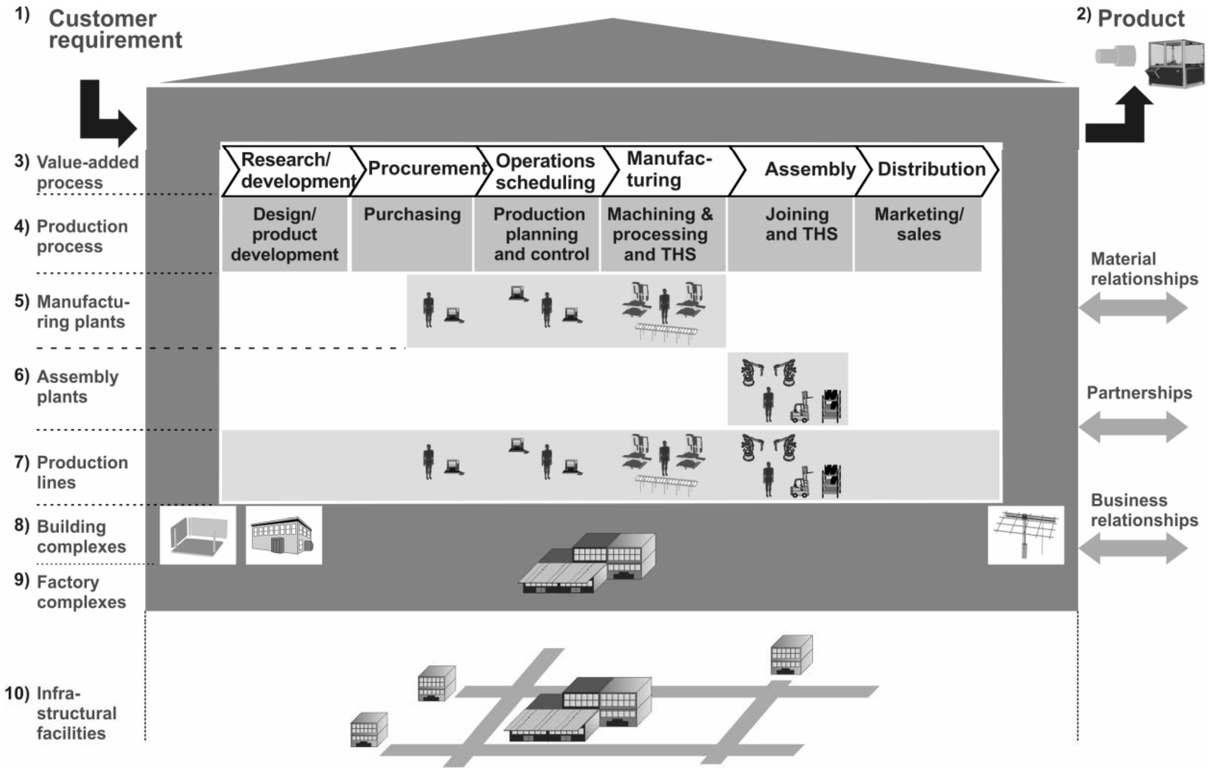



*Figure 3-10 A factory/production facility's product, processes and plants (SCHENK & WIRTH 2004)*

Figure 3-10 shows the value chain of a product and the different elements that take process, that can be classified in the PPR model and each will be explained with a small introduction (SCHENK 2010, P. 9)

For doing the customer order by the customer for the physical goods, first there should achieved the customer requirements (1) that are the fulfilment of the customer desires.

Product (2) – The result of working procedures that fulfil the demands of the client. (Product, assembly, components, repetitive components, raw materials)

Value-added process (3) – The set of all business activities performed to satisfy a client requirement; it is implemented by value-added units in the value-added chain (research, development, procurement, scheduling of operations, production, assembly, distribution).

Production process (4) – as explained before, all processes engaged in manufacturing products in a mix of human resources (workforce), technology (machinery) and organisation. It includes engineering / development design, buying, planning and control of manufacturing, machining and processing, THS, assembly, distribution, sales and service.

Manufacturing plant (5) – Production of individual components with buying, production planning and control through machining and processing equipment and systems, including transport, handling and storage facilities.

Assembly system (6) – Creation of component assemblies (system parts, products) using joining and assembly facilities (systems) including transportation, handling and storage equipment with purchase, planning and control of manufacturing (and restricted design engineering and sales).

Production line (7) – Integrating machinery and plants for various procedures of technological manufacturing (production lines) and assembly (assembly lines), including transportation, handling and storage facilities, with design engineering, buying, planning and control of production, distribution and sales.

Building complex (8) – the infrastructure of the factory with the technical systems necessary and the load parameters required. The building is where all the processes are done with all the technical systems like water, heating, ventilation, power, IT, safety…

Factory complexes (9) – Constructions with manufacturing lines and infrastructure connections

Infrastructure (10) – Installed at the location are the supply and disposal systems of the site and factory (energy, water, gas, transport routes, etc.).

(SCHENK 2010, P. 9)

### 3.2.3 Value Stream Mapping

All the actions required to bring a product through the main flows like the production flow from the beginning with the raw material supply to the customers with the design of this concept is called value stream. All the actions are taking into account value added and non-value added processes. Value stream works not only with the individual processes but more with the perspective of the big picture, enhancing the whole system not just small processes. The goal of value stream mapping is helping you to visualize and understand the information and material flow as the product or service travel through the stream value and this is supposed to be a paper and pencil tool. The mapping is the visual representation of the production's path from the supplier to the customer.  This map can then assist in identifying the real processing times, recognizing the real value and improving the waste (ROTHER & SHOOK, 2009).

Some advantages of the mapping value stream would be:

- Easy visualization of the flow of the manufacturing processes not just as a single process level.
- Helping on identifying the sources of waste.
- Providing a common language for the production processes.
- It uses lean manufacturing concepts.

- It shows the relation between information and material flow during the whole process of production.
- It describes how the plant should work to create flow.
- It identifies how is the actual processes and helps to change them in a future state-map.

(ROTHER & SHOOK, 2009).

This mapping recognizes different kind of wastes that are classified in different categories (ERLACH 2010, PP. 119-123, GÜNTHNER ET AL 2013, P. 141, WOMACK & JONES 2003, P. 43):

1. Waste of overproduction

2. Waste of inventory

3. Waste of transport

4. Waste of defects

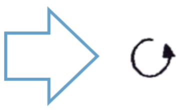
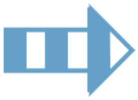
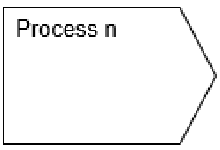
5. Waste of motion (movement of employees)

6. Waste of over-processing

7. Waste of waiting

The companies apart from the objective of the elimination of waste, another focus is enabling the continuous production flow in the entire value chain, focusing on the material and information flow. In the next Table 1, there are some symbols that are interesting for the reference model and will be introduced.

*Table 1 Symbols of Value Stream Mapping*

| Symbol | Represents |
|---|---|
|  | Movement of production material by Pull and it moves forward when the next process demands it. |
|  | Movement of production material by Push and it moves forward before the next process needs it. |
|   | One box equals to an area of flow of a manufacturing process |

In the Figure 3-11, an example of a value stream map is shown that is divided in the next elements (ERLACH 2010, PP. 32-33):

- Production processes (e.g. manufacturing or assembly steps)
- Business processes (e.g. order processing, production planning etc.)
- Material flow (e.g. transport of materials, parts or products between production steps)
- Information flow (e.g. data and information, which usually flow from business processes to production processes)
- Customer and
- Supplier

(ERLACH 2010, PP. 32-33).

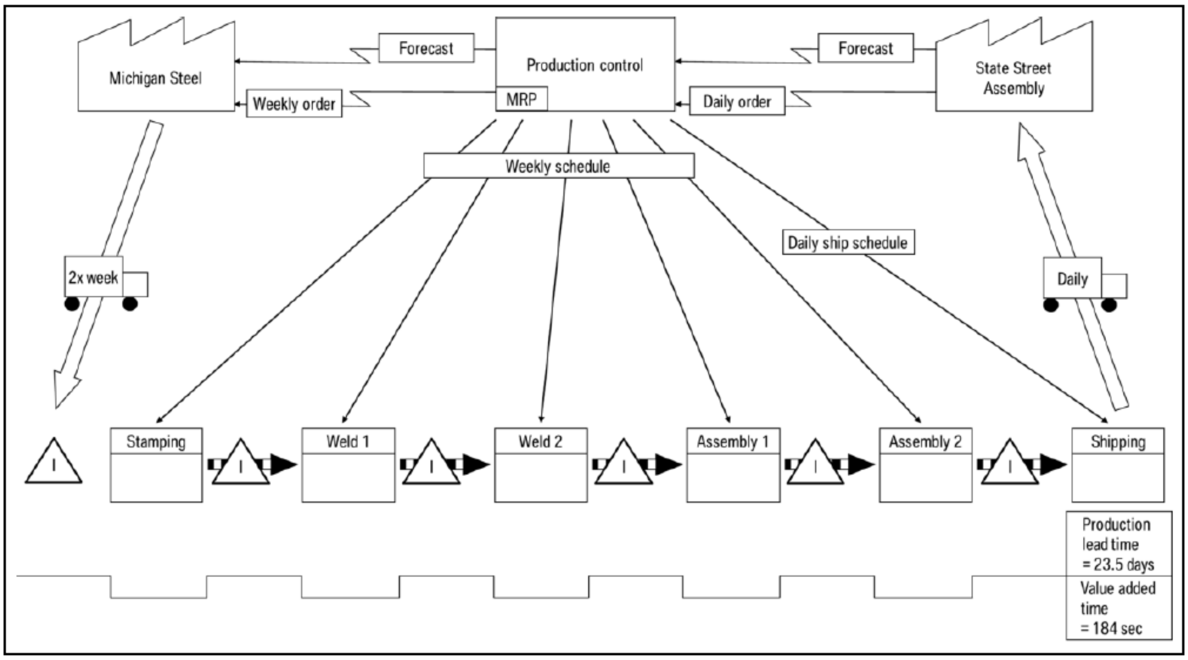



*Figure 3-11 Value stream map (WOMACK & JONES 2003 P. 317)*

# 4 State of Research

This chapter examines the state of the research that is necessary within the framework of this work in order to analyse the existing approaches, comparing them with the objectives of this thesis and seeing the lack of literature for the thesis' goal. There are not any document where they develop a model with the same ideas as the main objective that is having a clear understanding of how a factory looks, do a reference model of it and apply this model for modelling a specific factory quickly and easily. For doing this, the requirements of the reference model need to be defined, that means what literature you need to find for achieving the scope of work, and in this table there are some references from the bibliography having similar goals of the requirements needed. These requirements are explained in detail later in chapter 5.1, however there will be introduced now for the developing of the table.

*Table 2 Comparation of references*

| Topics / References | Modelling | Manufacturing Overview | Manufacturing Elements | Flow systems/ Relations | Production Planning |
|---|---|---|---|---|---|
| Plehn 2015 | focused | mentioned | discussed | investigated | not covered |
| Schenk et al 2010 | not covered | investigated | discussed | investigated | focused |
| Koch et al 2014 | focused | investigated | mentioned | mentioned | discussed |
| Hawer et al 2017 | discussed | mentioned | mentioned | mentioned | investigated |
| Rother & Shook, 2009 | investigated | discussed | mentioned | focused | mentioned |
| Agyapong-Kodua 2014 | focused | discussed | mentioned | mentioned | not covered |
| Singh, 2010 | not covered | discussed | focused | mentioned | not covered |
| Dallery & Gershwin, 1992 | discussed | mentioned | discussed | mentioned | not covered |
| Braun, 2018 | not covered | mentioned | mentioned | investigated | not covered |
| Kühns, 2018 | investigated | discussed | discussed | discussed | not covered |
| Helbing 2010 | mentioned | discussed | investigated | investigated | discussed |

not covered mentioned discussed investigated focused

## 4.1 Comparation of different references

PLEHN 2015 is one of the main interesting document because the purpose of the modelling is similar to our reference model, but it is not enough because it is too unspecific however the manufacturing modelling is a way to analyse and visualize impact changes. It begins with a brief analysis of the various areas of implementation for manufacturing science modelling and some requirements for manufacturing system modelling are introduced. After that, different modelling systems are presented like SysML, OPM and DSM and then it explains the metamodel in detail comparing it with the ontology design and doing the application of this model with a small example about a compressor shaft that it was mentioned before in Figure 3-6. The article concludes with a debate of prospective applications and outlines further study possibilities.

“Factory planning manual” from SCHENK 2010, as the main title mentions, is focused mainly in the factory planning but a lot of information was useful for introducing the manufacturing overview concepts, the structure of the main elements as well as a little bit of the actual processes of a factory plan. There is an interesting chapter about the material and information flow, where the different connections in the manufacturing system are explained. This book discusses the scheduling process of the plant with its many practical features. Previous planning approaches only emanate from the product model. New factory types can identify the requirements of a plant and understand the different elements, useful for the continuous planning of a factory.

Koch et al 2014 is focused on the change management of the industries and try to model the manufacturing system for giving more flexibility to the companies in “Structural modelling of extended manufacturing systems”. In this paper, they do not develop the processes of a manufacturing system and the different relations between them, and the model concept comes from the structural complexity management. They introduced the ExMS model, that was explained before but basically is the basic reconfiguration planning process with other subsystems. The system is based in the five domains – “cyclic influencing factors”, “CRP”, “product”, “manufacturing resource” and “manufacturing process”. At the end there is an implementation of the ExMS in a metamodel and it is applied in a case study showing the potential for constant reconfiguration scheduling procedures and generally an extended manufacturing system.

“An Adaptable Model for the Factory Planning Process: Analysing Data Based Interdependencies” from Hawer et al 2017 is a paper oriented in factory planning models. Therefore in this paper discussed about the structural complexity management and different continuous and modular process models. After this, the planning tasks are described with the background of expert interviews and then there is an explanation about a software tool to design process models, applying it to a case and ways to improve it in the future.

The book called "Learning to see: Value Stream Map" from ROTHER & SHOOK, 2009 is a useful literature because it explains the importance of seeing the relation between material and information flow within the production. This book can help to create a value stream map for helping in every area of the production. The objective is to differentiate between waste and value. The last part of the document is about the future state of the production, how it can be improved, and how it is improved with the results. Then also there is the implementation of the model for the management, which steps to do and how should be done. At the end there is an appendix with all the symbols and how they can be useful.

AGYAPONG-KODUA ET AL 2014 focuses in the paper "Recipe-based Integrated Semantic Product, Process, Resource (PPR) Digital Modelling Methodology" on the PPR modelling. It presents a 'recipe-based' approach to modelling based on ontologies with capability to rapidly define and select resource systems meeting product and process requirements. First it introduced the digital tools that are currently existing for modelling, specifying the requirements need it for the PPR model and explaining in detail what the product, process and resource are. Finally as almost always after a model development, there is a case study and the summary and outlook.

In the book "Introduction to basic manufacturing processes and workshop technology" from SINGH 2010, there is a detailed explanation of the different manufacturing processes. In the first chapters, they explain topics about the industrial environment and manufacturing companies. After that, it starts more into the factory plant and layout and finally finishes with all the different explanations about different processes like welding and mentioning all important elements for a safe and successful production.

Dallery & Gershwin, 1992 in "Manufacturing flow line systems: a review of models and analytical results" describe some models and results of the manufacturing flow literature. Therefore there is an extended explanation on production systems and how each different production system influences in the models. Although these models were to deep and not really interesting for the modelling part of the thesis, but they were relevant to identify different production systems. Finally there are some directions for future research.

In the master thesis of Braun, 2018, submitted in the production management and logistics institute in the Technical University of Munich, there are some terms about logistics and manufacturing relevant for the thesis. The thesis is focused in the developing of a methodology for evaluating and compare the different value streams, however the most relevant topics from this literature are the basic background of logistics and value streams.

As well, the thesis of Kühns, 2018 was interesting to taking into account, because the idea of modelling was similar and it was taken into account for the different possibilities of modelling. It is focused on a reference model for maintenance but there are a lot of concepts related to manufacturing as well as the modelling process. This structure has similar topics to this thesis and therefore at the end of it, there is a validation of the model.

Finally the last document to remark is “Handbuch Fabrikprojektierung” from Helbing 2010. In this book there are a lot of information about the factory, what kind of factories exist and how to divide the different production areas. When he was describing about the factory, it is necessary to explain the different flows and relations that were interesting for the literature and which processes are needed in a factory.

# 5 Reference Model

Each reference model can be used to develop other models (HARS 1994, P. 15). In Figure 5-1, there is the main idea of the thesis for the reference model represented. In this case, from the literature and particular cases of manufacturing systems, the reference model was developed in an abstract way and once the reference model is there, it has the advantage to adapt for each particular case of the different manufacturing systems from the companies. Having different backgrounds and examples is required to provide a high quality reference model that contains all the knowledge (SCHWEGMANN 1999, P. 53). Therefore, a reference model must have some overall validity, but it must also be defined in such a way that it can be implemented without alteration (HARS 1994, P. 15).

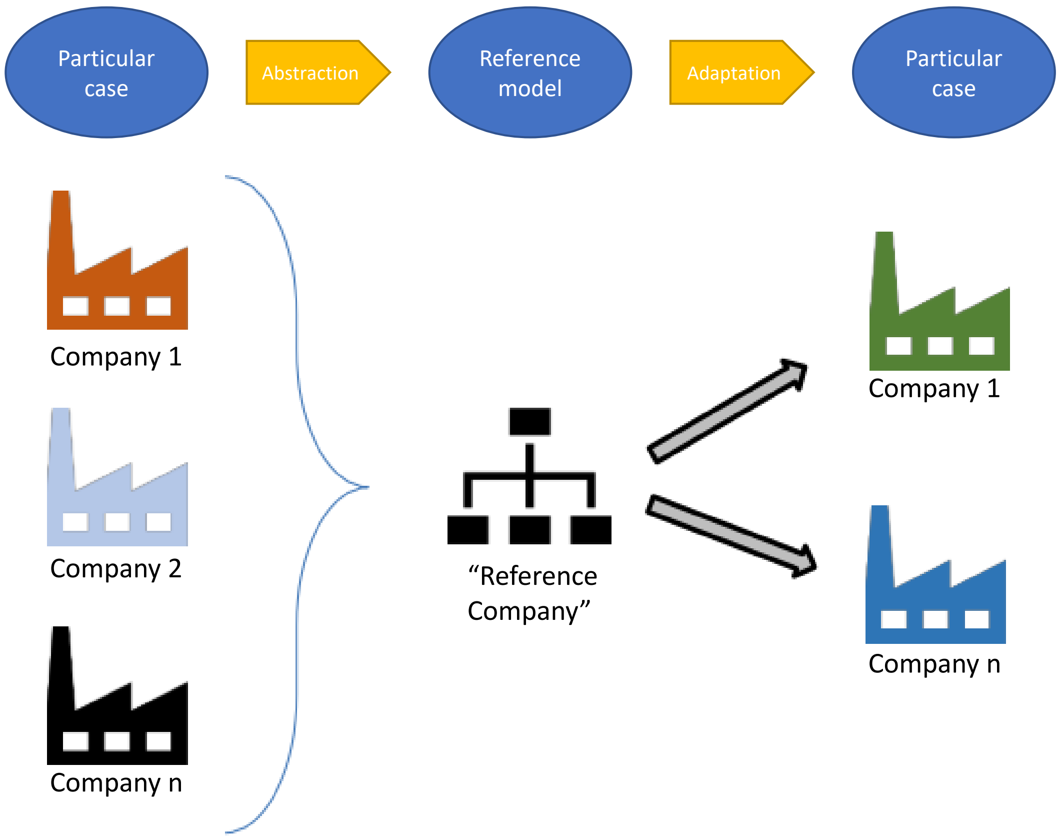



*Figure 5-1 Reference model for companies (GAJEWSKI 2004, P 14)*

## 5.1 Guide & Requirements

In this chapter, the requirements (r) for a reference model of production systems are first developed. These requirements have been already introduced in chapter 4, but in this section will be explained more in detail.

The main features of a reference model are its overall validity and recommendation (HARS 1994, SCHÜTTE 1998, SCHWEGMANN 1999, VOM BROCKE 2003)

r1: The type of modelling must be suitable for any kind of manufacturing company.

The type of modelling must be suitable for every manufacturing company in order to be able to correctly represent the elements in the different production systems. The purpose is to help every company in the industry and that is why the necessity of the validation for all production systems.

r2: The general overview of a manufacturing system needs to be defined and how it is divided in different production areas.

The structure of the manufacturing system should be visualized in the reference model, representing the different areas of the production and the different connections between them in the different levels.

r3: Manufacturing system activities and components are to be defined and allocated to the various production fields.

The reference model should depict and assign to the production fields the duties that occur in a manufacturing system. Production elements that are related with other components must also be included and given to the distinct fields in the reference model.

r4: It is necessary to define the relationships and interconnections between the different elements and between the production areas and the different flows.

The connections between the different production areas need to be represented in the model because one of the key points in the reference model is to understand the required flows for the achievement of the product and in order to do that, value stream map was one of the tools to visualize everything better. For doing this, it is necessary to understand the different types of connections and also all the processes inside manufacturing system need to be defined.

r5: It needs to be clear that the manufacturing planning is required also in way of current production.

With this requirement, it means that the planning processes for building a factory or design this manufacturing system is not the important point here, but the planning of the main manufacturing processes and the continuous update of each interface is a key area in the model.

### 5.1.1 Procedure

To define and develop a reference model, there will be five phases for the construction process, starting from the definition of the problem to the application of the model with the validation (SCHÜTTE 1998). In Figure 5-2 can be seen the different steps for the process and will be introduced in this section.

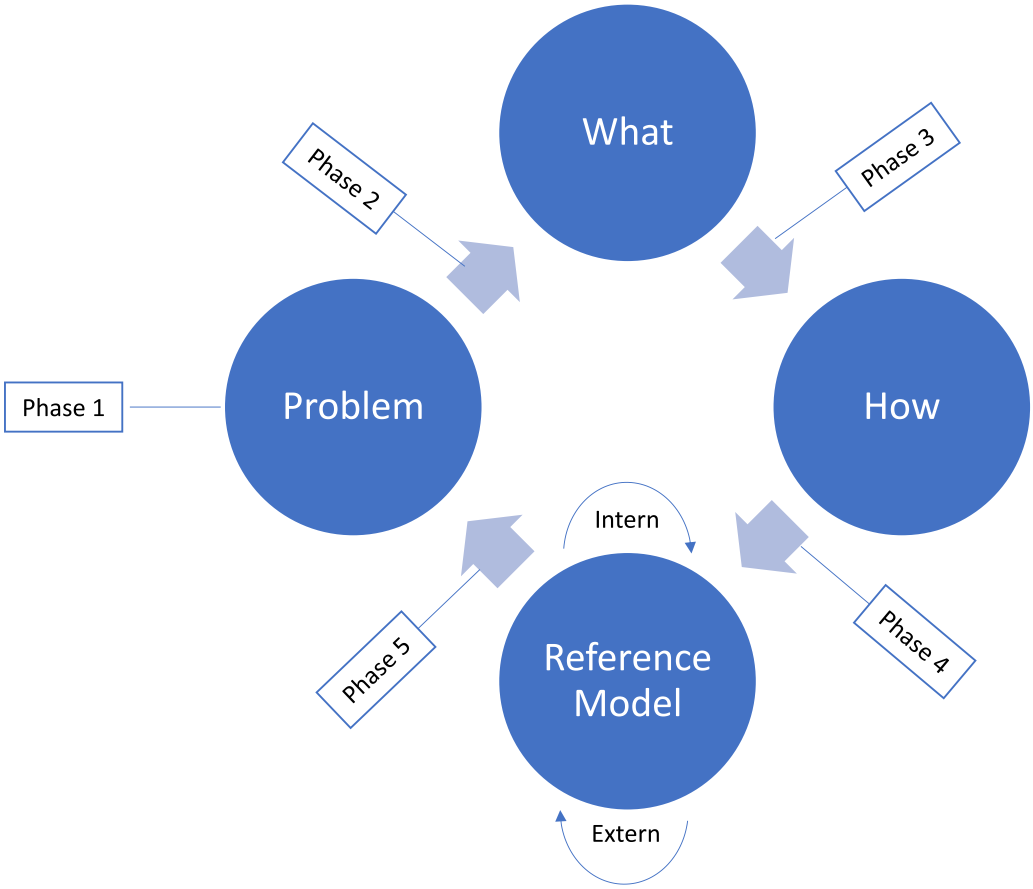



*Figure 5-2 Procedure of a reference model (SCHÜTTE 1998)*

Phase 1: Problem definition

The first phase is to define the problem and understand why this model needs to be done. In this section the problems of the reference model are analysed and classified for seeing the best approach to take and using feedback loops during this process.

Phase 2: Construction of the reference model frame

In this second step, the construction of the reference model frame is done, defining the characteristics to design later on this model. This would be the "what" of the procedure, what it is going to be modelled and supported from different standardized models or techniques from the actual literature, with building blocks, behaviours or symbols.

Phase 3: Construction of the reference model structure

Here starts the how of the procedure, how is going to be modelled. The third phase needs to take into account the “what” for doing the “how”, because now the reference structure needs to be done and in this case, recognizing all the processes to do this and the different connections between each other and which way of representing them.

Phase 4: Final completion

In this phase, it is time to finish the reference model, taking into account the internal and external connections within and between other models. It is relevant to have a consistent model to applicate in the different industries with the same procedure and certainty.

Phase 5: Application

The last phase is one of the most important ones, because it is the moment to realize if the reference model actually works. The application to a real example means the control of the model and see if there should be any improvements.

(SCHÜTTE 1998)

## 5.2 Development

Phase 1: Problem definition

As it was explained before, the problem definition would be the first phase of the modelling (SCHÜTTE 1998). In this case, the problem is the modelling of a manufacturing system, recognizing all the elements of the production plant and the best way to connect everything together to show and visualize a manufacturing system. The real problem is the recognition of the elements in a manufacturing system in the different production companies and try to get a reference model that covers every kind of production system and after that, specialized for each to have a better understanding of the processes and be aware of the change management in production (BAUER 2019)

Phase 2: Construction of the reference model frame

The construction of the reference model frame would be the next step and in our case would be the model overview, which frame will be used in the model and the reference model would be based on four core levels. They will be explained in detail in the next section but basically the first level would be the **planning**, related with the actual process planning inside manufacturing, then the different **processes** related to the main **value adding process** where the manufacturing processes and the assembly processes would be done. The reference model will be focused on the assembly processes more than in the actual manufacturing. Finally the last interface would be the **IT interfaces**, because it is an important aspect of the manufacturing companies.

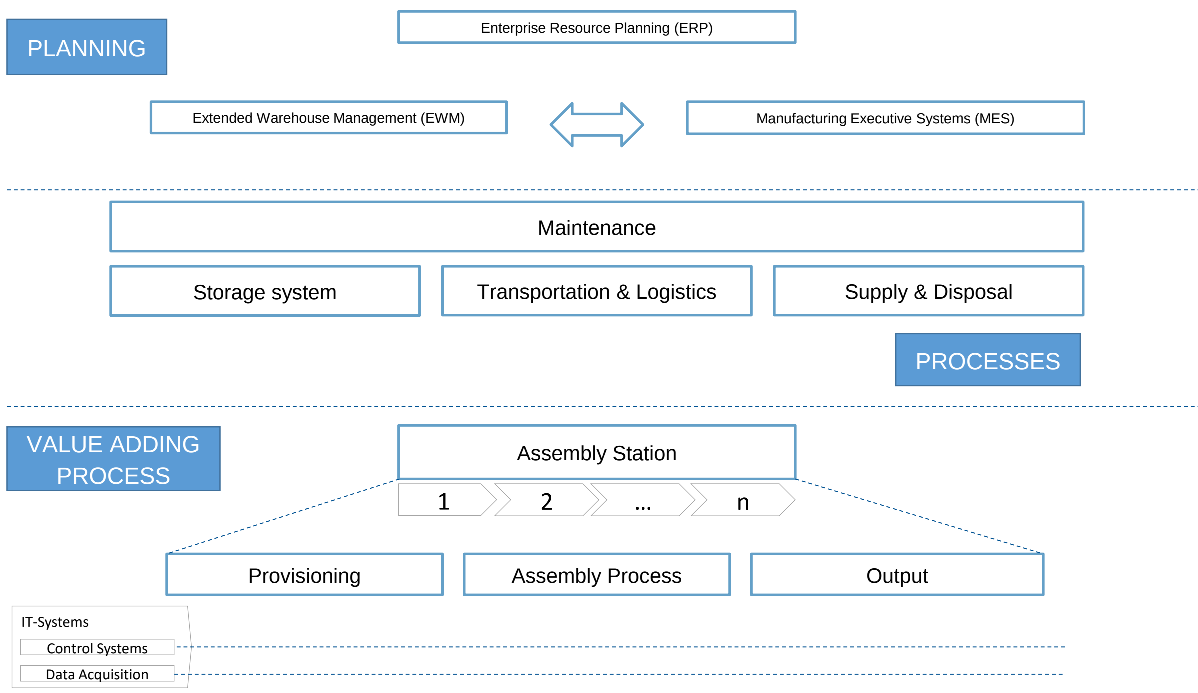



*Figure 5-3 Simple overview of the reference model*

Phase 3: Construction of the reference model structure

The phase three is the how the model is going to be represented. In this case, the model was based on the PPR modelling method and Value Stream Mapping for developing the structure of the reference model. In the Figure 5-4 is shown the main structure of the model, with an overview of the areas that will be in the model. In this phase, the different areas of a manufacturing system are recognized, and they are explained later in detail. They are divided in the planning level into **Enterprise Resource Planning** (ERP) and after that, **Extended Warehouse Management** (EWM) and **Manufacturing Executive System** (MES). In the level of processes, they were divided in four categories that are important in the manufacturing system as **maintenance**, **storage system**, **transportation & logistics** and **supply & disposal**. Then the last two areas are the value adding process where the **assembly station** is developed with the PPR structure and the **IT interfaces**, using discontinuous lines in the model and relating them with the whole model. The value stream mapping symbols are used as well as the idea of the structure techniques through the whole reference model.

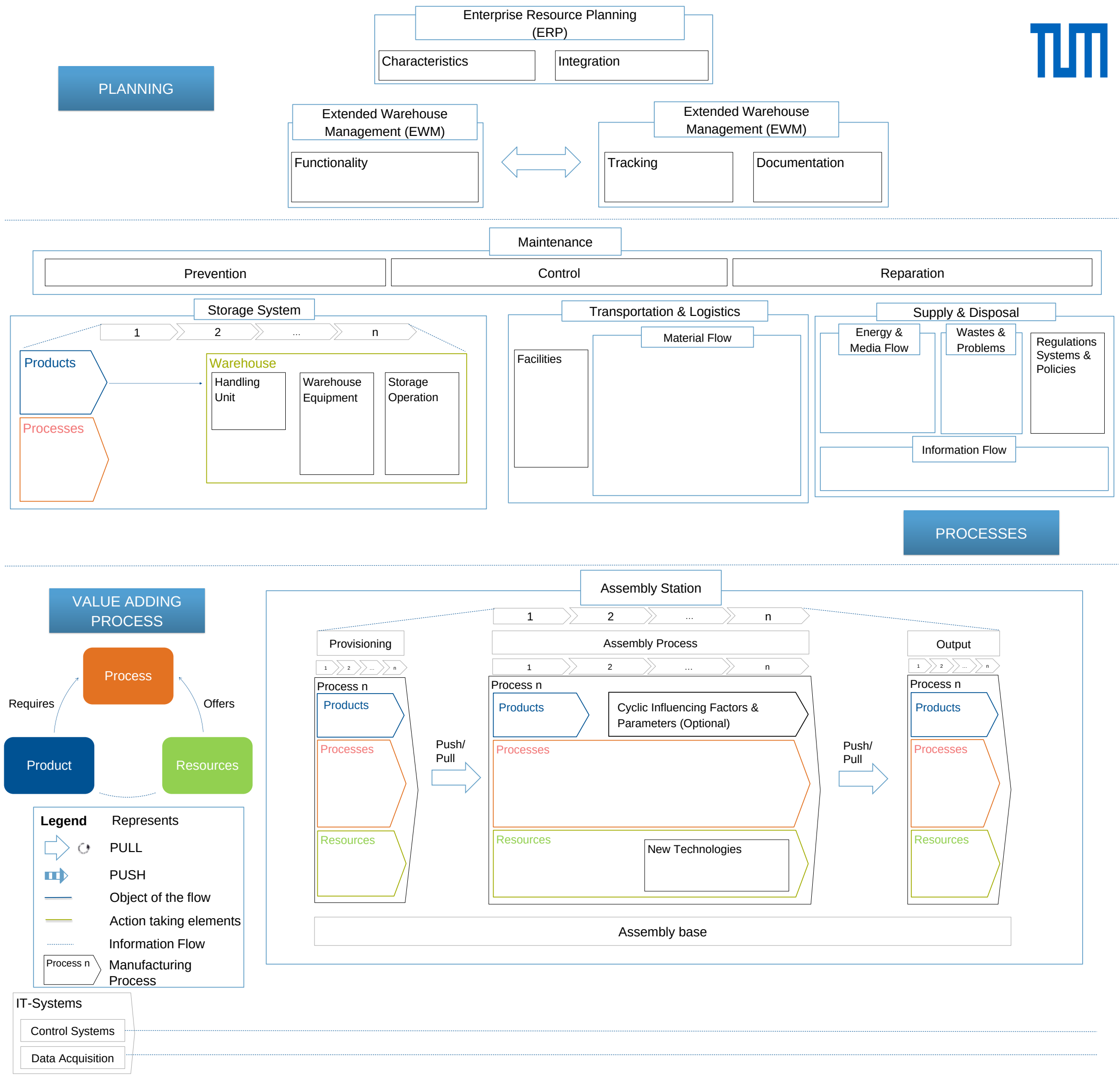



*Figure 5-4 Reference model overview*

Phase 4: Final completion

The fourth phase of the procedure is the final completion of the reference model. The main goal of this is finishing the model, with all the **elements** inside as it is shown in Figure 9-1 and in the attachment documents "Reference Model for Production Systems.ppt" and during the development in this section when each area is explained in detail. The source of these elements is described in Table 3. In this phase also is the time for doing all the interconnections between the different area and elements, therefore there will be defined the different flows like material, information, energy & media flow.

The application phase will be explained in section 6, because the validation of the reference model will be detailed there.

For the structure of the model, there is a legend (Figure 5-5) to understand the model. These colour structure and symbols were used for the better visualization of the model as well as a way to model the production systems with the help of PPR modelling and value stream mapping. In this case, the model has been categorised in three types of domains actually, on the one side the “Product” in blue, that requires a “Process” to be achieved and with the help of the “Resource” that offers the required elements to comply with this process. On the other hand some symbols were inspired from Value Stream Map and were used for the material flows between the different areas as well a colour structure based on the previous technique, for differentiating between the elements inside the processes. The manufacturing process was used in the assembly station area, for explaining that each manufacturing process is divided in the PPR.

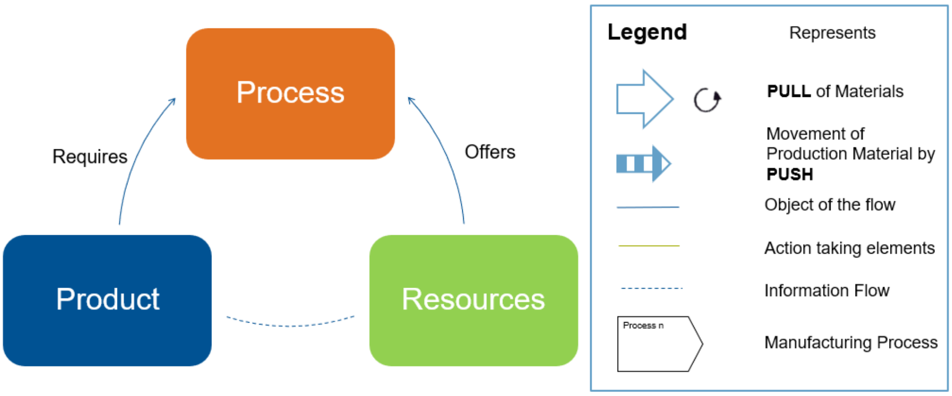



*Figure 5-5 Legend for the model*

### 5.2.1 Planning

The planning area was divided in two different levels and three different topics. The first level is the ERP, where all the different tasks of the company are organized and structured for the running of a manufacturing enterprise. Inside this level was introduced the next level, because inside ERP there is an area called manufacturing which is in charge of all the manufacturing processes and this area was divided in two other sections of manufacturing planning that were interested for our manufacturing system model.

On the one hand there is the topic EWM, in charge of the logistic planning processes mostly and on the other hand would be the MES, responsible for the manufacturing planning processes. These two are relevant because they are in continuous work during the manufacturing process.

### 5.2.1.1 ERP

In Figure 5-6 is described some relevant elements of the ERP. This area is split in two main sections, one is about the characteristics, what the ERP is actually doing in the manufacturing system and the other one is about the different areas that are integrated in this software.

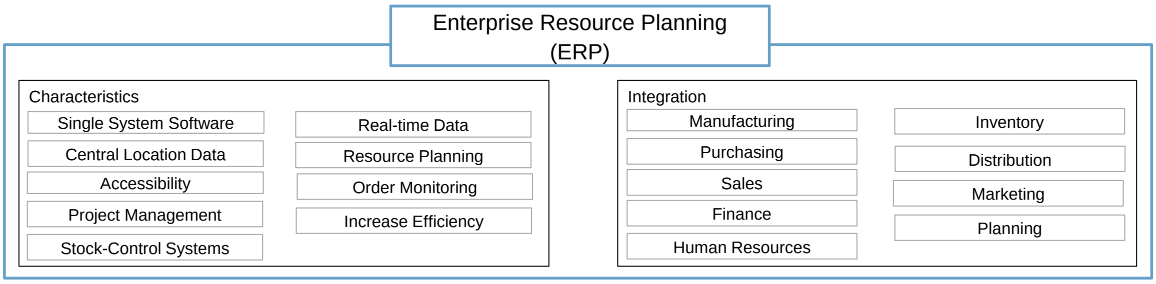



*Figure 5-6 ERP elements*

### 5.2.1.2 EWM

The EWM elements are shown in Figure 5-7 and these elements are representing what function has this topic. Basically it is in charge of the logistic processes and the material flow planning, therefore relevant tasks in here would be the storage planning or the transportation requirements for the movement of this material flow as well as taking care of the supply of materials and the delivery of the products using inventory management for example.

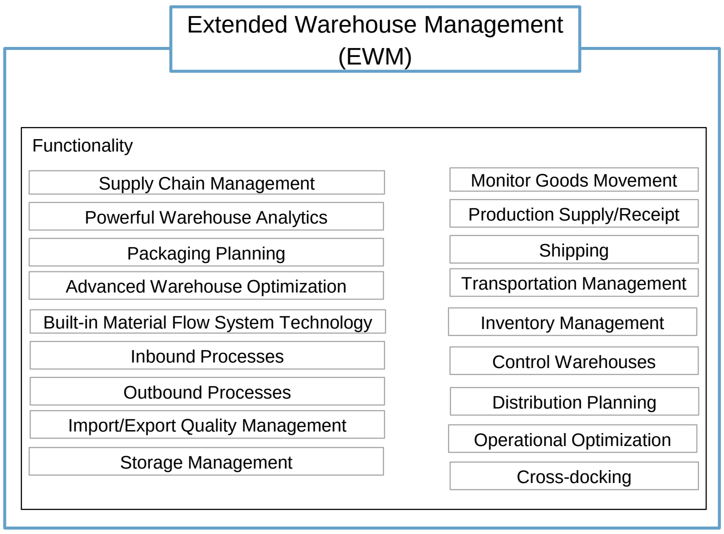



*Figure 5-7 EWM elements*

### 5.2.1.3 MES

MES is a tool used for many manufacturing companies because it really helps with the manufacturing planning and it is a continuous task during a production system. It is divided in two sections (Figure 5-8), on the one side the tracking part of the production with real time data and planning the job schedule and which resources are needed for the processes. On the other side is the documentation part, where all the planning processes are saved for checking them for example the production definition, which are the steps to follow to produce it, which kind of production is required, etc.

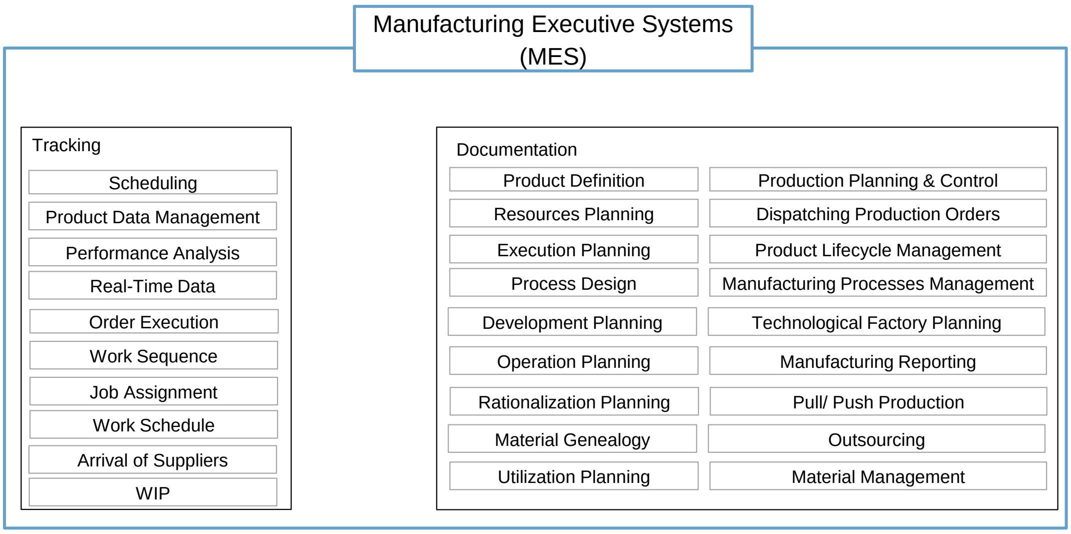



*Figure 5-8 MES elements*

## 5.2.2 Processes

In this section of the model, there are the processes required for the value adding process. It was divided in four main areas, in which maintenance is above all of them because it is related with the other three. The other three areas are storage system, transportation & logistics and supply & disposal and will be explained later in detail. At the same time, all these processes are interconnected between each other because some elements are necessary or related somehow to other elements from another area.

### 5.2.2.1 Maintenance

Maintenance is a relevant area of a manufacturing system because during the manufacturing process is important to take into account breakdowns of the machines for example, because it influences a lot in the production planning and execution if there is a broken machine that was required for the product supply. In this case the maintenance is related with all the areas because in each area there are resources that need to be controlled. As we explained before, the maintenance was divided in three main sections. The first one is the prevention of problems, where elements like lubrication, cleaning or safety equipment are important for the prevention of defects. Then there is the control section, where inspections or fault tolerances are elements of this topic and it is about the control of all the resources. Instead of measurements for preventing, this is more about the routine of the maintenance in the manufacturing context. The last section is about the reparation, because once the problem is presented in the production system, the problem needs to be solved as soon as possible and here the elements to take into account are spare parts or manuals for solving the problems for example. In the Figure 5-9 is shown all the elements inside maintenance.

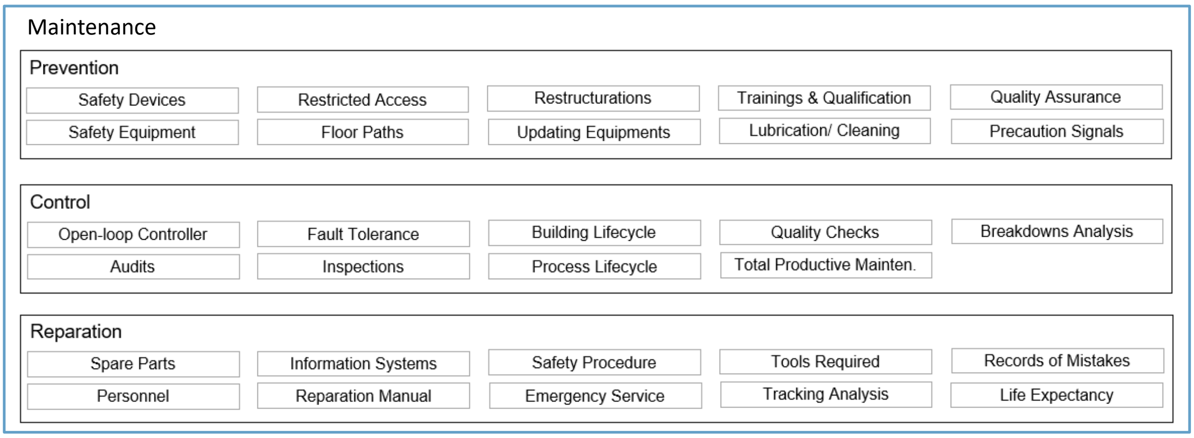



*Figure 5-9 Maintenance elements*

### 5.2.2.2 Storage System

Another relevant area in the production system is the storage. In this case the storage is divided in different processes as is shown in Figure 5-10, with the blocks with numbers that means that can be more than one process in the storage system and each process with the PPR model follows the procedure of the figure. It is divided in the PPR model with different elements of the storage area and focusing in the resources that is the warehouse where some elements that are required for achieving the goal of this area are presented. The warehouse is separated in handling unit like pallets, warehouse equipment like the storage shelving and finally the storage operation, therefore the required element for moving the products like a forklift. Finally the two boxes at the end of each product handled in the storage system, that are the removal from the storage and the delivery to the next process/ area.

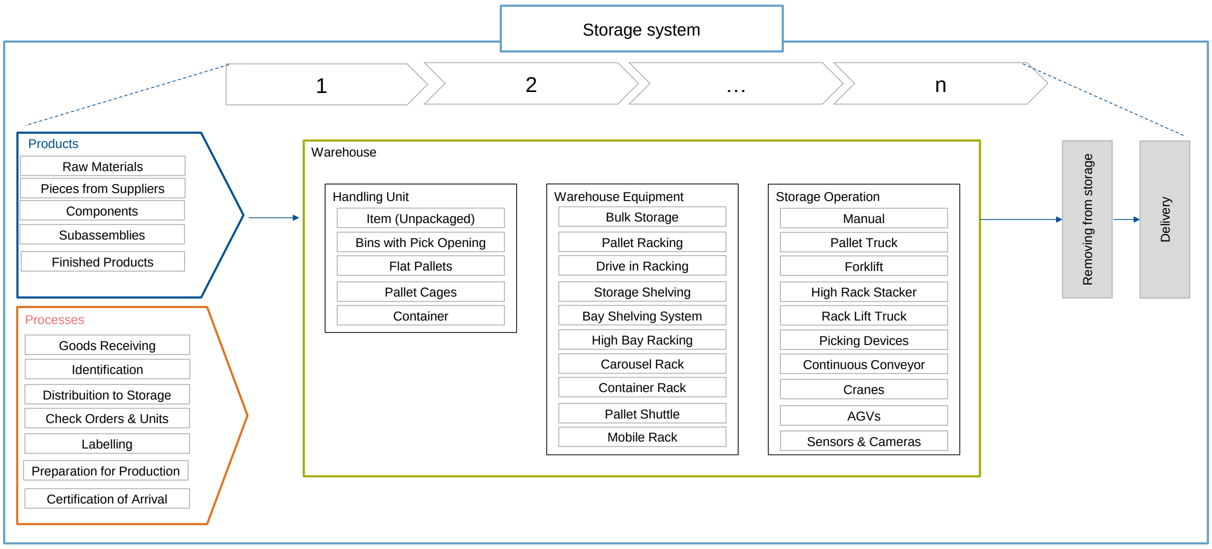



*Figure 5-10 Storage system elements*

### 5.2.2.3 Transportation & Logistics

Transportation & Logistics is another section related with the material flow. Therefore this section is divided in facilities required for this movement of material with elements like cranes or sorting systems, relevant in a production system for the flow and production of the materials. The structure used in the material flow as it is shown with the colours legend is first of all the object of the flow in blue, the main goal of the material flow and the action taking elements to achieve the goal that is green. The goal of the material flow is the transportation of goods with required elements like personnel, AGVs or picking devices. The material flow is always related and connected to supported elements like information systems where the data with the execution orders are presented. The steering logic is relevant in this section because depending on the logic, the push or pull system will be used, as it was explained before and with influencing factors like cost or the production schedule.

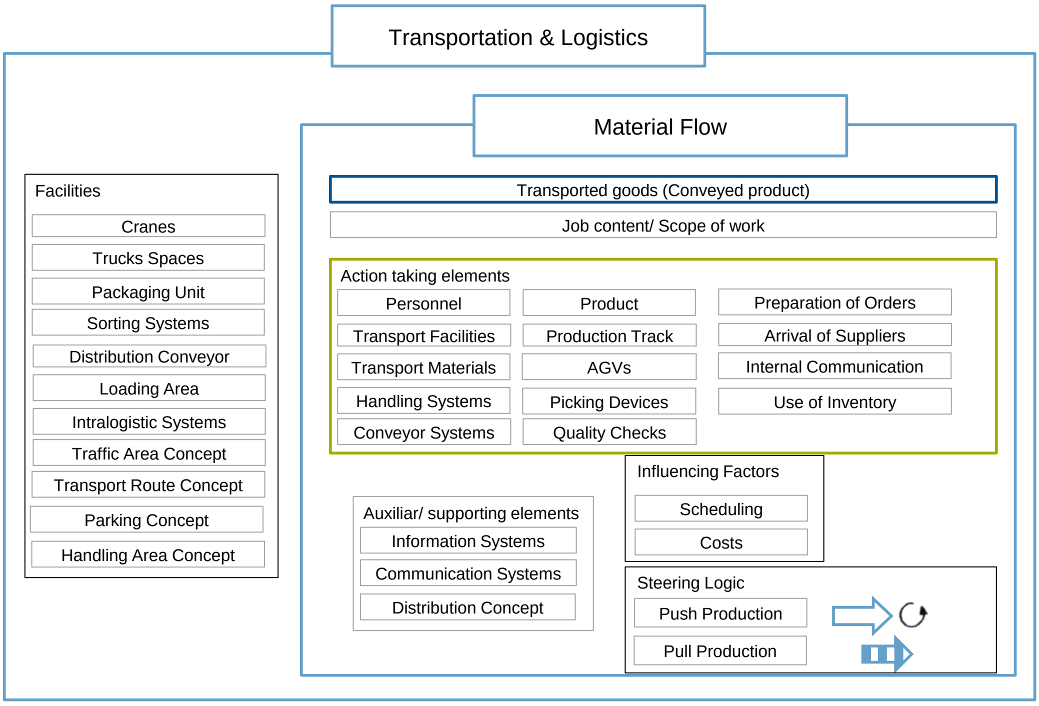



*Figure 5-11 Transportation & Logistics elements*

### 5.2.2.4 Supply & Disposal

The last area that was mentioned is a combined area with different elements that are important to the adding value process and is interconnected with the other key areas. Here there are two main flows like Media & Energy flow and Information flow as well as wastes & problems and regulation systems & policies. The flows are structured like the material flow, with the main goal of the energy and media flow that is the continuous supply of the energy and media source with action taking elements like the water supply and the power supply and auxiliary elements like water pipes or information. The other goal for information flow is the transportation of the information like the tasks and scheduling data and resources like telecommunication systems. Wastes and problems is an area where elements that are inside a production system need to be taken into account like the pollution, the product scrap, recycling and the optimization of the resources. Finally the regulation and policy systems, because a production system needs different elements like safety regulation, emission control devices, etc, that are presented in the current manufacturing system and they need to be modelled as well in all the manufacturing systems.

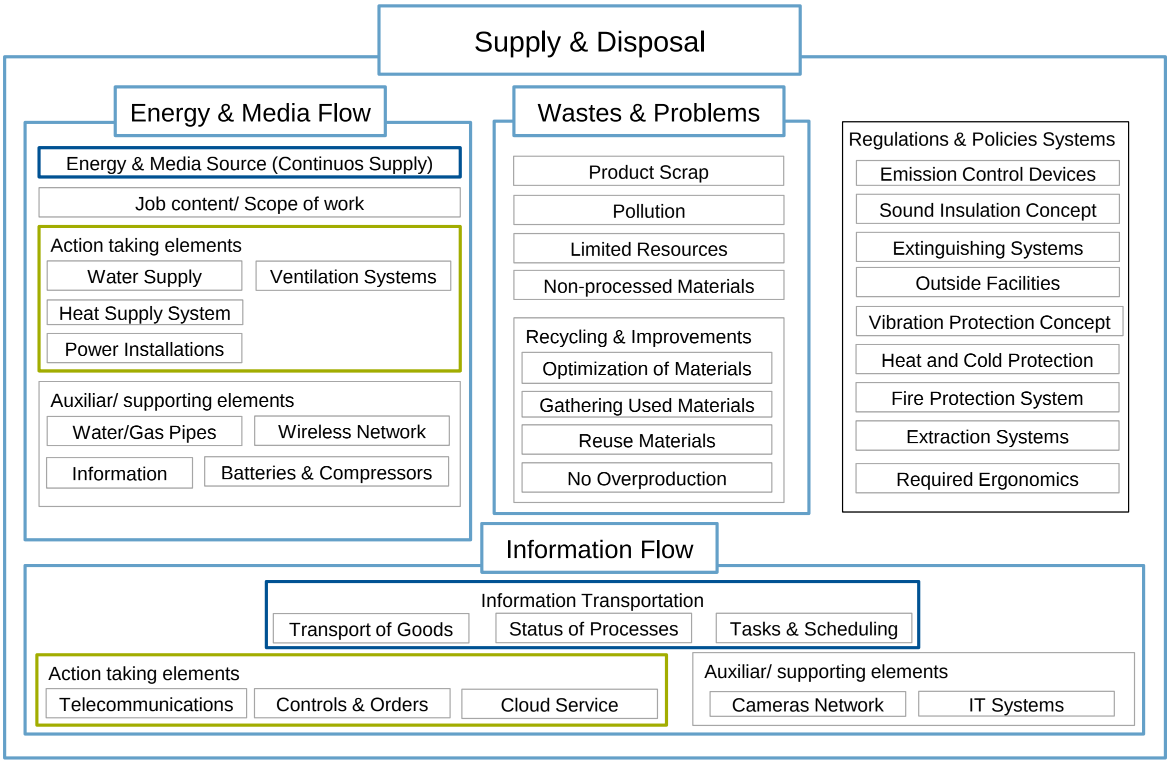



*Figure 5-12 Supply & disposal elements*

## 5.2.3 Value Adding Process

The value adding process is the main and most important area of the model, because it is the most focused in the actual manufacturing system. Due to the difficulty and generality of a manufacturing system, it was focused on the assembly of a manufacturing system. The value adding process is the area where the product changes and gets more value for the supply of it to a customer need. As it was explained before, this area is interconnected to all the different areas.

### 5.2.3.1 Assembly Station

The assembly station as is shown in Figure 5-13, it represents that in a manufacturing system can be more than one assembly station and inside each assembly station is structured in three different aspects. First of all the provisioning, then the actual assembly process and finally the output. Inside these categories, there are different processes like is represented with the blocks with numbers. These manufacturing processes will be modelled with the PPR model and between each process there will be a material flow that can be push or pull as it is visualized with the arrow.

First of all, the provisioning stage in the assembly station is the processes to prepare the actual assembly process afterwards. In this part there are some elements divided in products with raw materials or subassemblies for example, with the processes required for the provisioning like the material supply and the product preparation for the actual process with some resources like the tools required or the workforce.

Following this stage, the assembly process starts with different processes with the same elements inside the product domain however mentioning the influencing factors and parameters of the products, because in this area, each parameter like the conditions of the product or the number of units to be produced will influence in the assembly process. There are some processes like cutting or joining and with the required resources like operators, robots, QR codes, etc… In this resource domain, the new technologies during the last years are mentioned also because the knowledge that influences in the way of manufacturing something is relevant and taken into account in the reference model like 3D printers, big data or blockchain, that are already implemented in many current manufacturing systems and improve the efficiency.

Finally the output stage that is structured equally to the other two stages and is the step where the assembly process is finished or almost and the product needs to go somewhere, therefore the product is stopped in this area for some time to prepare the delivery to the next process or checking the quality of it. In the product domain there are the same elements as before but the processes are finishing, labelling or quality checking for example with resources like personnel and QR codes.

In this reference model, below the different areas the assembly base is mentioned, because there are some elements that are required always and in each process like safety devices, furniture or others.

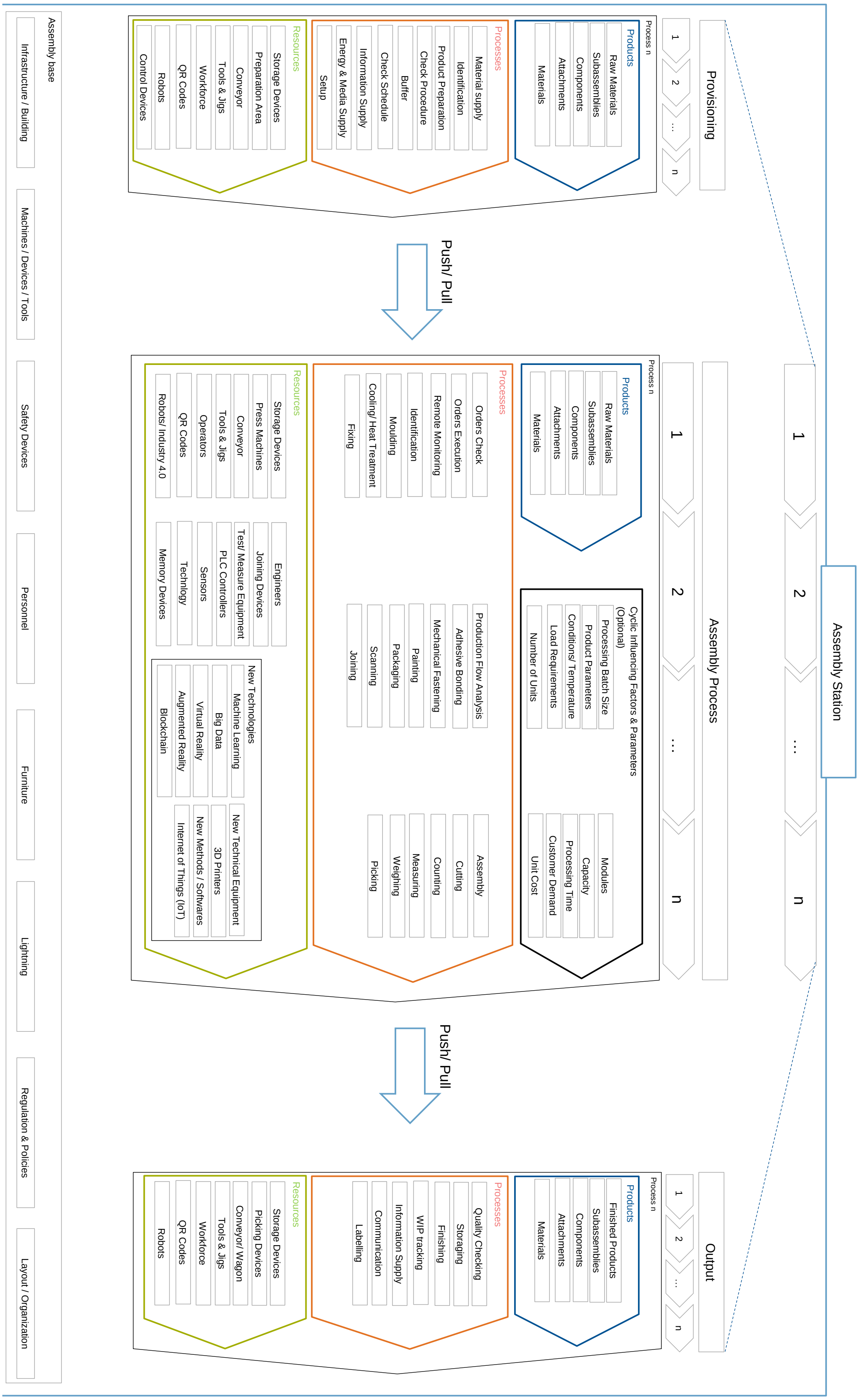



*Figure 5-13 Assembly station elements*

## 5.2.4 IT Systems

Finally the last area to describe from the reference model is the IT Systems that is a complicated area and will be introduced. Nowadays all the manufacturing companies are using IT systems because it is everything related with too much data and computers and therefore to mention this was relevant.

In the model, the IT systems are not visualized with each process because it was difficult to link each element to the IT system but it is visualized in a way that represents that each element can be linked to the IT system if it is required. The discontinuous line means that is representing information flow and the two key elements are control systems and data acquisition. In the validation of the model is linked to each element that requires this IT system.


*Figure 5-14 IT Systems elements*

# 6 Validation

For the creation of a reference model, as it was explained before in the procedure, the last step is to apply it to a case study and see if it works and how to improve it. In this case, the reference model was applied to a learning factory from the Institute of Production Management and Logistics of the Technical University of Munich.

## 6.1 Case Study

The case study was about a learning factory of an assembly station of basic stations. The product was an electrical engine with internal gearbox ratios that is used in electrical doors for trains or golf trolleys. In the Figure 6-1, there are the different products that could be produced in this assembly station.

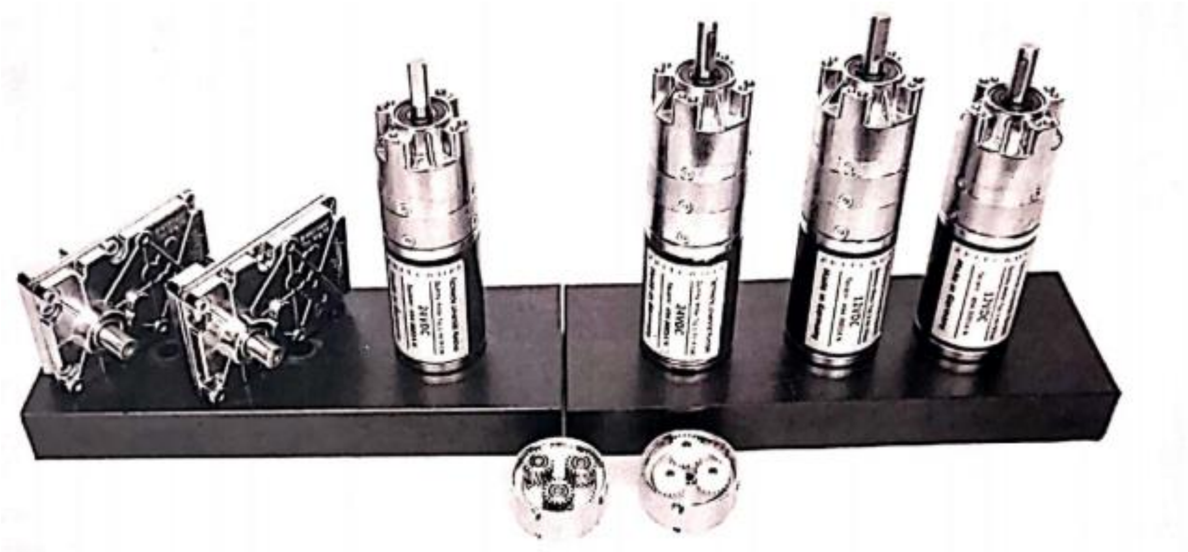


*Figure 6-1 Electrical engines from the learning factory*

## 6.2 Model Validation

During this validation, the reference model was used for helping to visualize the model of this learning factory (see Figure 6-2). Due to the simplicity of the case study, some elements were not taken into account but probably in other examples would be relevant. The model was structured in the four assembly stations that were in the factory and interconnected with the planning from the MES and the IT systems as well as the different flows and the storage.

The planning area is based only in the MES, because in this case study the only part that was shown from the planning was the ipad that controls everything from there, how many units to do, when and how. This model also helped to realize of some elements that were not in the reference model at first and some other that were not really relevant. This planning area is a copy of the MES from the reference model, focusing in the tracking part because the documentation was not in the learning factory.

After that, the four assembly stations are introduced and the differentiation between each other. First of all the assembly station 1, always connected to the storage from the factory. All the assembly stations are divided in the three categories explained before and the PPR model. The products are the different parts like the planetary gear of steel that needed to be assembled for producing the 1$^{st}$ finished subassembly. Each product was supplied from the shelves that were connected to the storage. In the provisioning category, the supply and identification of the material were done as well as the scanning of the bar code to start the processes. On the assembly process part, the different assembly processes like joining the different materials were done to finish in the output, where the control of the 1$^{st}$ finished subassembly and the scanning and movement to the next station will be prepared.

Each station is connected to the different flows. The arrow between each station is the push movement between the different stations as it was explained before. This movement was manual between stations and the information flow and energy & media flow between stations are required. As it is shown in Figure 6-7, the information flow is connected with each station through the discontinuous lines that represent the information flow and at the same time is connected to the planning process (MES), because the ipad is continuously analysing the assembly process and this MES has all the information in real time. The elements inside are the status of the next processes and information about the first finished subassembly with the help of the personnel communication or Kanban.

On the other side, material flow transports the finished subassembly from assembly station 1 with the help of the personnel and the energy & media flow for each station is focused on the power supply for the tools and electricity and the ventilation system of the learning factory.

The storage is in the factory, having some shelves with open bins with the material required, and once the material is finished, the personnel through the Kanban asks for more material. This means that the steering logic is pull and therefore it is visualized with the symbols from Value Stream Map .

For each station has a similar structure but different goals as it is shown in the different Figure 6-3, Figure 6-4, Figure 6-5 and Figure 6-6, there are different processes to finish the product but the idea is the same. In the last assembly station 4, the product is finished and packaged and is delivered to the customer with the help of transportation & logistics area.

During the whole assembly process, there is the assembly base where basic elements that are in all the processes are mentioned like the fire extinguisher for the safety of the factory, the lightning, the layout (4 assembly stations in line) of the factory that influences on the production system and the furniture required in each assembly station.

Furthermore the IT systems are represented like in the reference model and interconnected through the information flow with the elements that are necessary to be related with data acquisition and control systems. These elements can be the ipad, that is continuously obtaining new data or the screwdriver with sensors, that gets data as well as the storage shelves in assembly station 3, where the storage has sensors in the rolling system to ask for more material supply through the electronic Kanban for example.

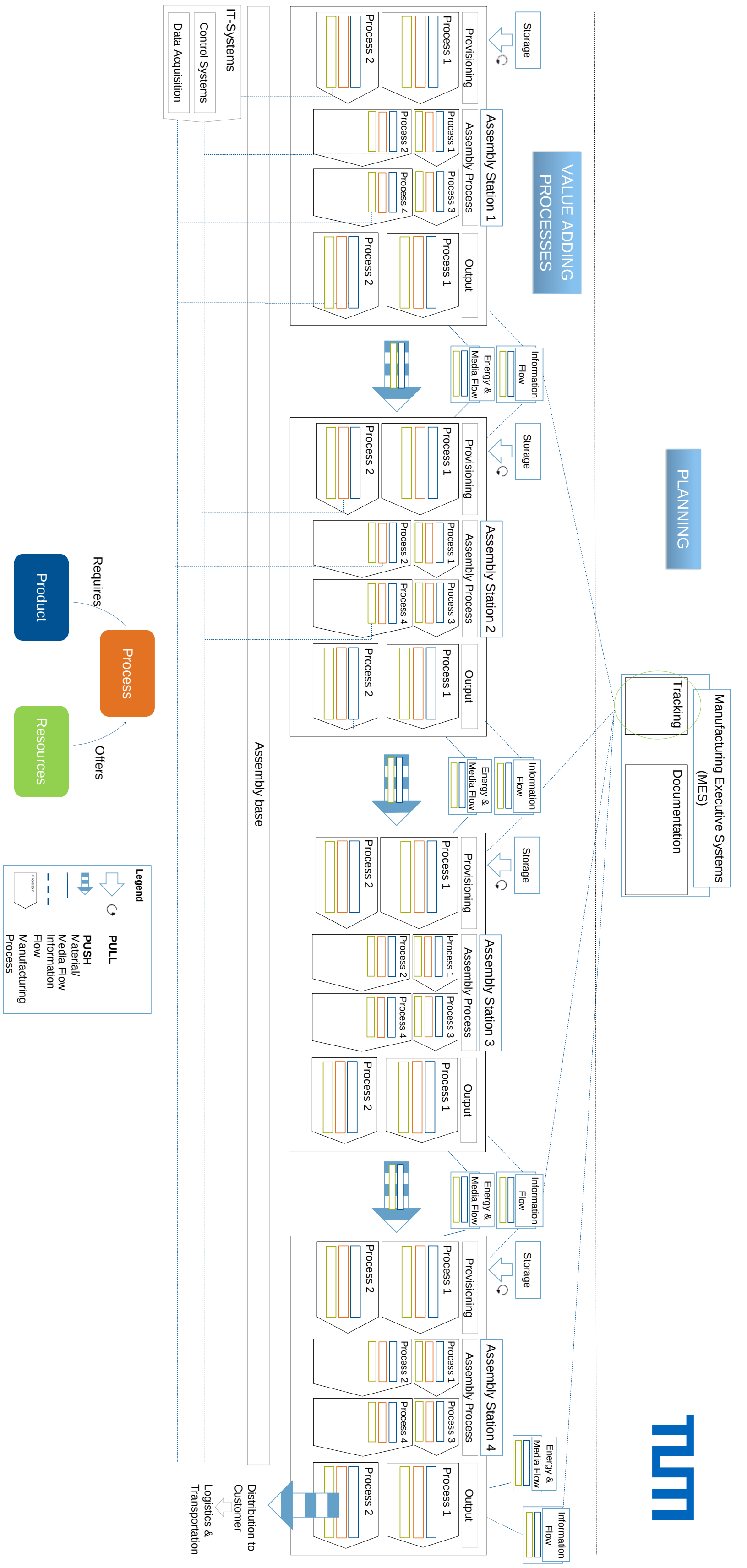



Figure 6-2 Validation model overview

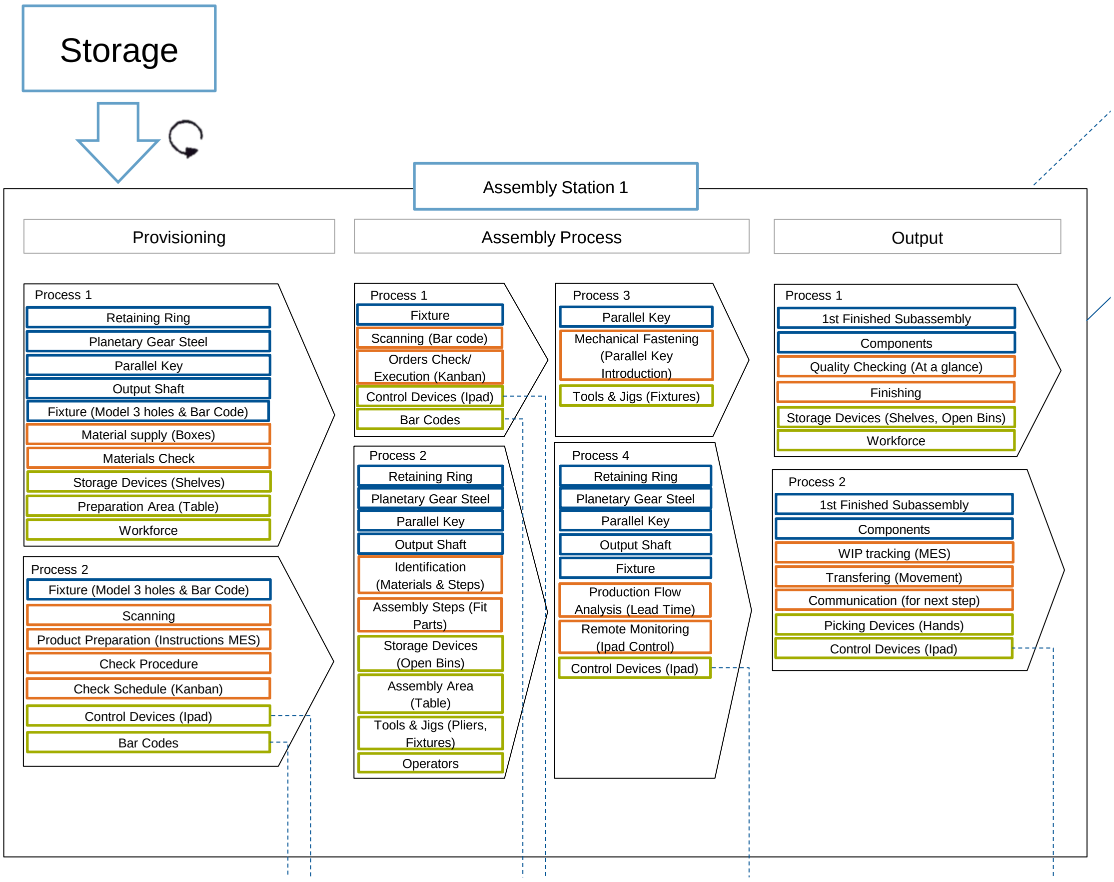



*Figure 6-3 Assembly station 1 elements*

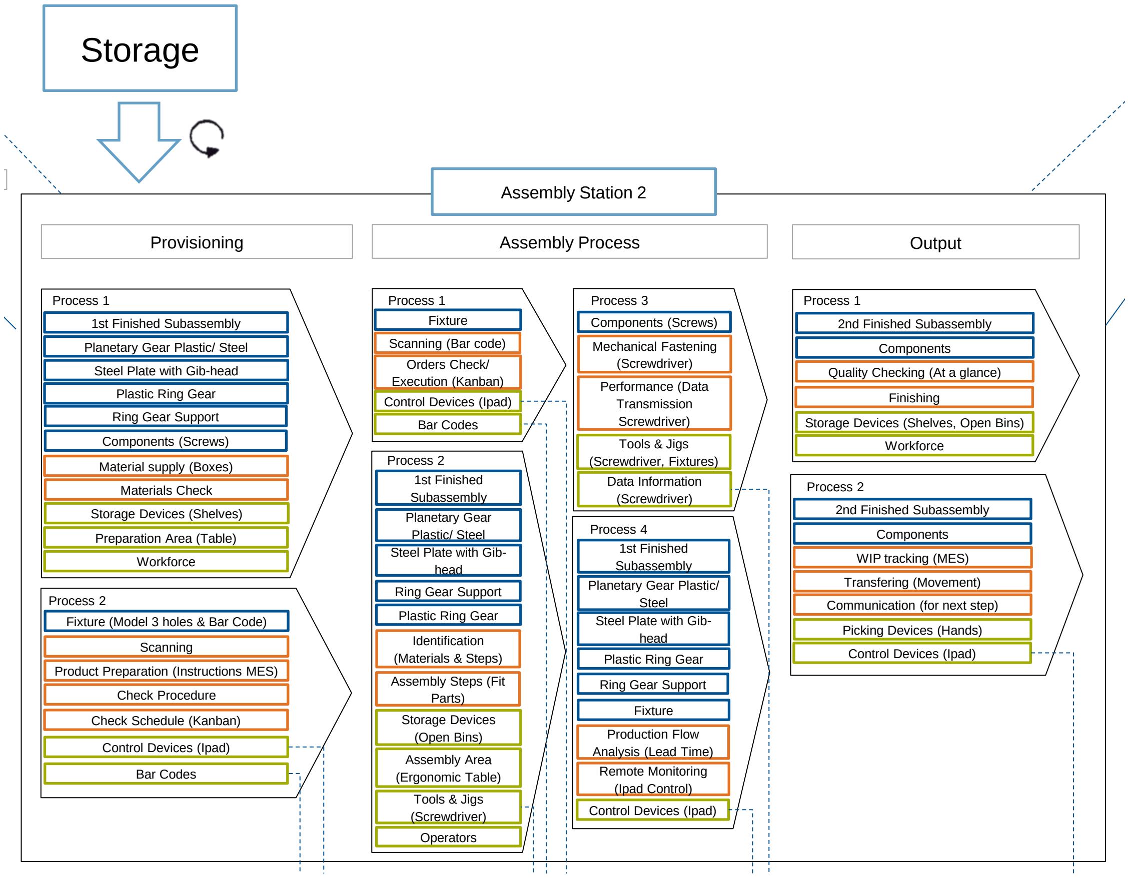



*Figure 6-4 Assembly station 2 elements*

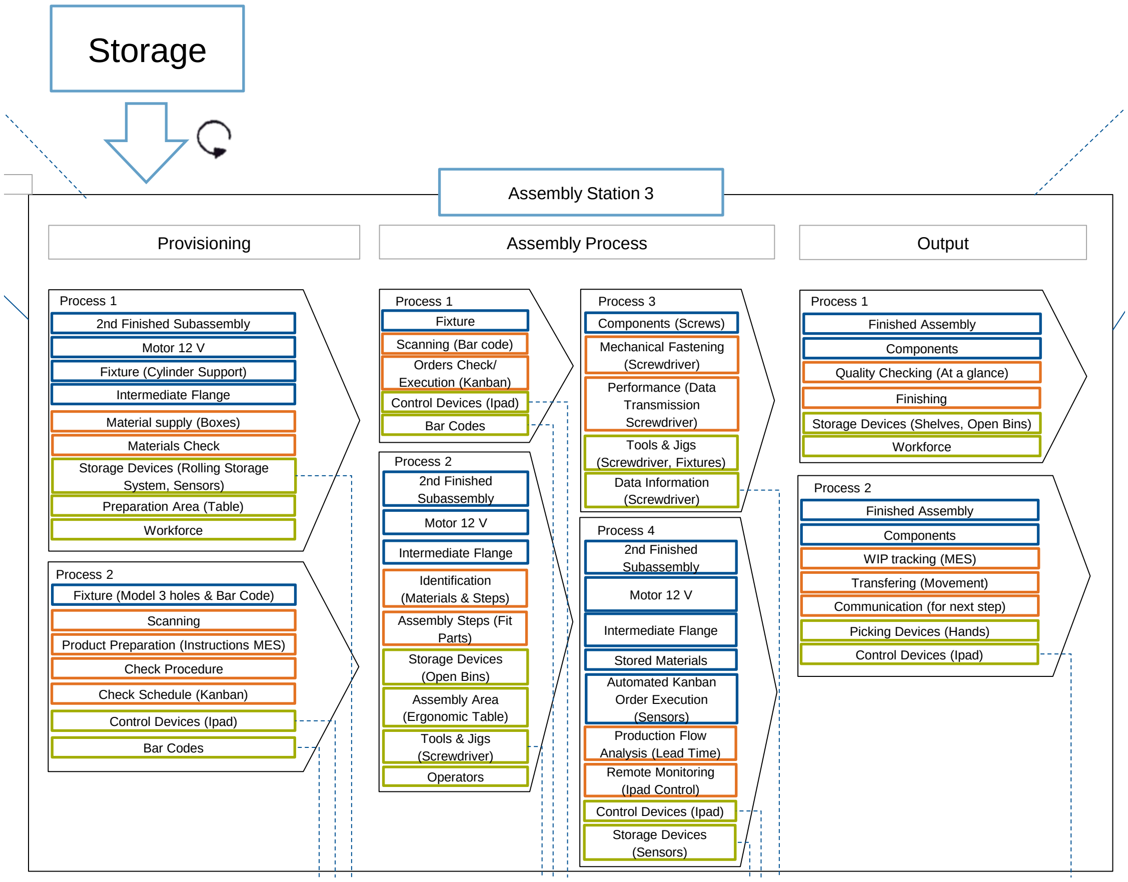



*Figure 6-5 Assembly station 3 elements*

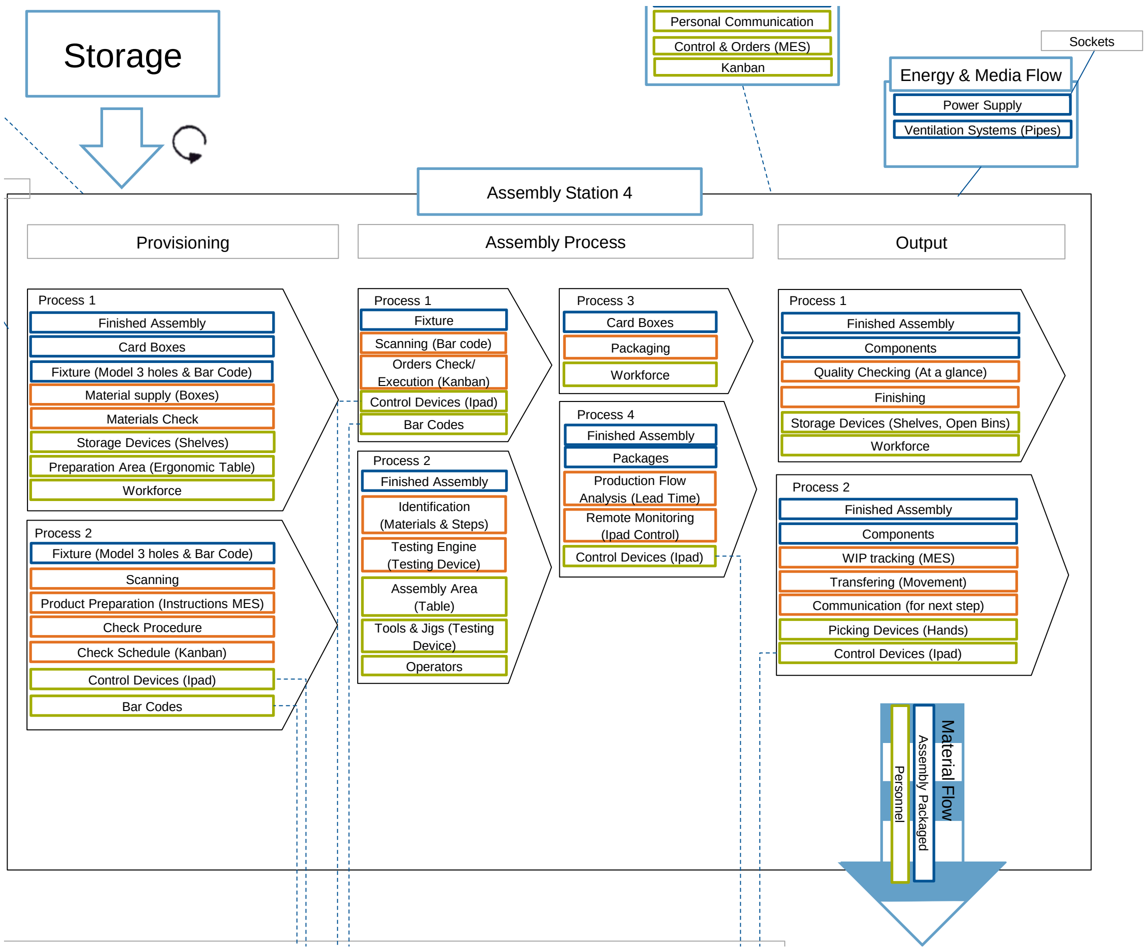



*Figure 6-6 Assembly station 4 elements*

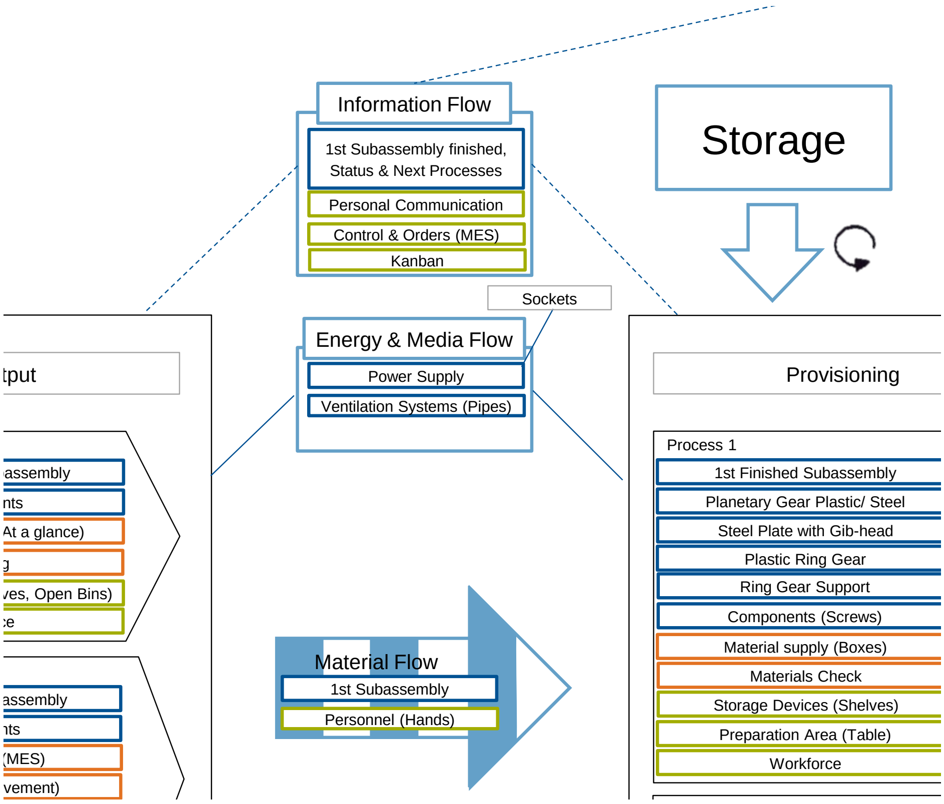



*Figure 6-7 Flow systems elements*

## 6.3 Changes to Reference Model

Thanks to the validation of the reference model, the model had different changes to be improved for the future. In this section some aspects will be introduced to show how the validation model influenced.

One of the changes was the structure of the assembly station as a whole, because before the validation, the PPR model was structured with all the elements inside each domain and it was difficult to identify which processes were together. After that, all the different processes inside each category were represented in different boxes with the PPR model inside them.

Another change was the lines from IT systems, because before the validation there were some different elements that did not make sense to be there and they were deleted for the final version.

Finally there were also changes in elements inside the assembly processes because before the application of the model for example, there were not control devices in the resources domain, which are an important element in the case study because of all the information managed in the ipad.

# 7 Summary and Outlook

During this thesis, the reference model of production systems was developed. This idea came up because of the gap in the current literature of modelling a production system in a factory, taking into account all the elements from an abstract view but with the idea to visualize easily and quickly the production system of each manufacturing company. The motivation for it was to be useful in the future and this reference model needs to be used in the different manufacturing companies based on the assembly stations. The goal from the company is to identify quickly its own manufacturing system and afterwards, model it with the structure of the reference model, identifying and improving in those aspects that it needs to be focused.

For achieving this, first of all was developed the reference model, after a lot of research and once the model was done, the thesis was structured with the goal of explaining and understanding easier the reference model and its advantages. Because of that, it was required to do an introduction about the basics of production. In this case manufacturing was described more in detail, explaining about the different factories, what types of factories there are, the different production systems related to the different flow systems required for production and a small description about push and pull manufacturing. Other topics that were described are intern logistics and maintenance, explaining the importance of them in a manufacturing system.

After this introduction, there was also an introduction for modelling, explaining why modelling could be a good option to represent a manufacturing system and an explanation about the different modelling methods that there are in the current literature as well as the modelling methods that were used finally in our reference model.

Once the terms to understand the reference model were explained, there is a comparation of the different used references in the thesis, and why this thesis is necessary for the production industry.

Finally the explanation of the reference model is developed in detail, with figures showing the overview of the reference model and the elements in detail for each area. The reference model can be seen in attachments section, however was easier to explain in this way. In this case, the reference model was developed based on the metamodel definition and the PPR modelling structure and the value stream map. This was the best way to visualize all the elements and for connecting each other with a meaning. Due to the variety of manufacturing systems, the reference model was more focused on the assembly processes.

To improve and certified this model, there was an application of it to a case study related with an assembly station of a small electric engine. This case study is explained in detail with the different improvements of the reference model, and showing the validation model that was developed thanks to the support of the reference model. This validation model was described also with an overview picture of the whole model and with more detailed pictures about each area. This factory was divided in four assembly stations in line with basic processes and with the different connections to the material, media and energy and information flows, the IT interfaces and the planning area of the production system.

After the successful development of the reference model there are different topics for future researches. Three different areas will be introduced but probably it has more paths to be followed.

In the first case would be about the validation, because probably this model could be validate as well for more production plants, for testing it and also with expert interviews, to see and identify all the elements in an assembly station. The more applications of it, the better will be developed and improved for all kind of production systems in the future.

In the second possibility, there is a big opportunity to focus on the manufacturing part of the production system. This was the main goal before starting the thesis, but after seeing the variety of manufacturing plants, it was difficult to do a model to take into account everything. Therefore a good extension of the research could be to implement this for manufacturing plants, not only focused on assembly stations.

The last option and the extension of this research would be related with change management. One of the main purposes of this thesis is easily model the production system of manufacturing company for being flexible to change impacts. Therefore with the support of this model, it is better to assess the different impacts in a production system when there are changes in the industry. Changes in manufacturing systems are induced by a multitude of change causes such as external influences, engineering changes, new production technologies and because of that, the manufacturing companies need to be ready for changeability.

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# 9 Attachments

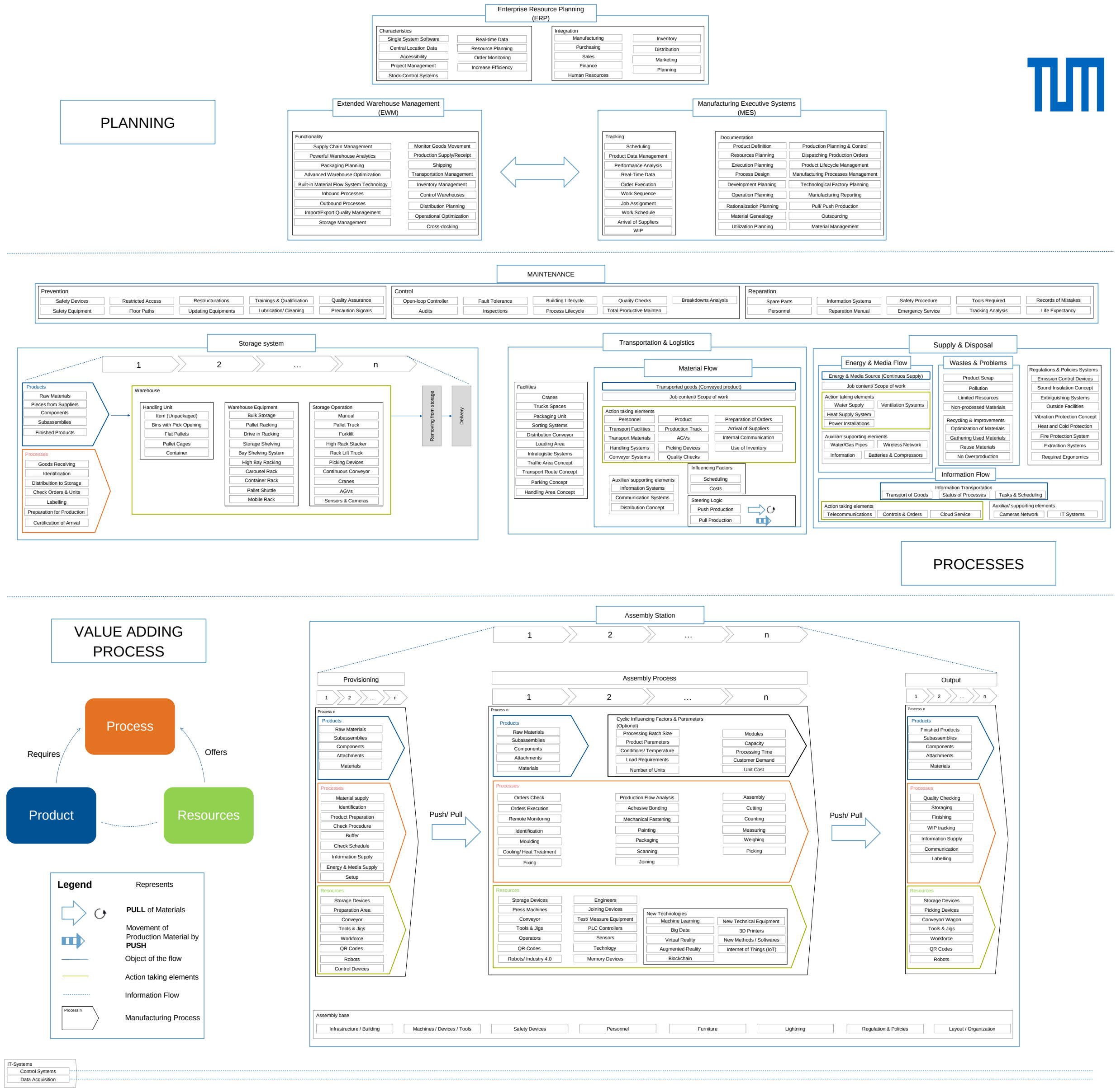


*Figure 9-1 Reference Model for Production Systems*

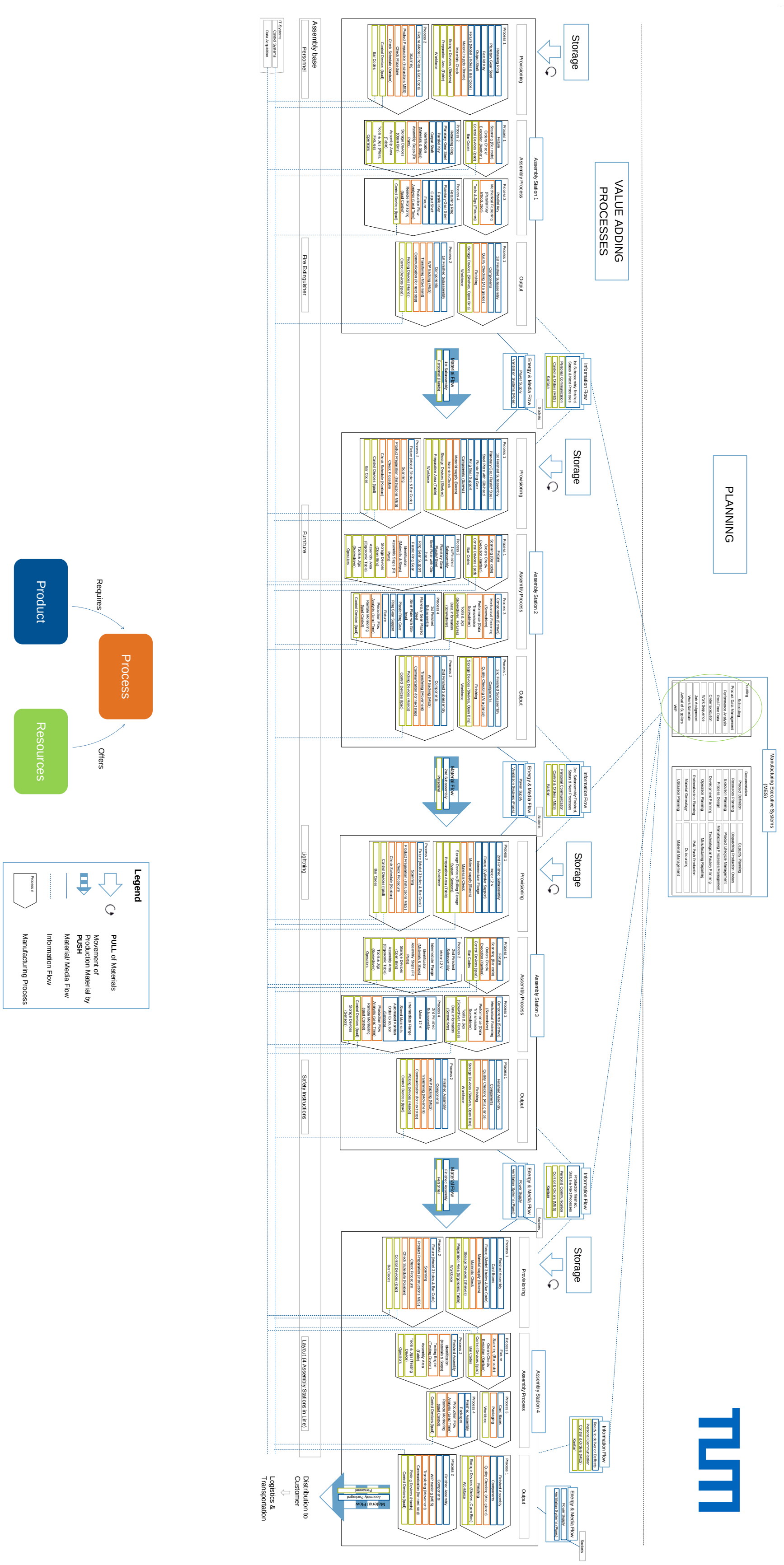


Figure 9-2 Validation Model of the Production System

In the following table, the references of some elements from the reference model for production systems are shown. To create and develop the model, the different references were used, however the different discussions with Bauer as well as other elements that were defined from the knowledge of the different researches are not introduced in this table.

*Table 3 References of the elements from the reference model*

| Element | Reference |
|---|---|
| **Enterprise Resource Planning** | (LABARRE 2019) |
| **Extended Warehouse Management** | (FERNÁNDEZ 2019), (HUTTER 2019) |
| **Manufacturing Executive System** | (ROUSE 2019) |
| **Maintenance** | |
| Safety devices | (SCHENK 2014) |
| Trainings & Qualification | (NOFEN 2006) |
| Quality assurance | (NOFEN 2006) |
| Open-loop controller | (SCHENK 2014) |
| Fault tolerance | (NOFEN 2006) |
| Inspections | (NOFEN 2006) |
| Process lifecycle | (SCHENK 2014) |
| Building lifecycle | (SCHENK 2014) |
| Total productive maintenance | (KÜHNS 2018) |
| Tools required | (SCHENK 2014) |
| Information systems | (NOFEN 2006) |
| **Storage system** | |
| Goods receiving | (HOMPEL ET AL 2007) |
| Identification | (HOMPEL ET AL 2007) |
| Distribution to storage | (NOFEN 2006) |
| Delivery | (NOFEN 2006) |
| Handling unit | (SCHENK 2014) |
| Products | (SCHENK 2014) |

| | |
|---|---|
| Raw materials | (WIENDAHL ET AL. 2013) |
| Subassemblies | (WIENDAHL ET AL. 2013) |
| Finished products | (WIENDAHL ET AL. 2013) |
| Warehouse equipment | (GUDEHUS 2012) |
| Storage operation elements | (NOFEN 2006) |
| **Transportation & Logistics** | |
| Personnel | (SCHENK 2014) |
| Transportation facilities | (SCHENK 2014) |
| Communication systems | (NOFEN 2006) |
| Intralogistics systems | (NOFEN 2006) |
| Scheduling | (NOFEN 2006) |
| Conveyor systems | (NOFEN 2006) |
| Traffic area concept | (NOFEN 2006) |
| Transport route concept | (NOFEN 2006) |
| Handling area concept | (SCHENK 2014) |
| Material flow | (SCHENK 2014) |
| Packaging unit | (SCHENK 2014) |
| Use of inventory | (HOMPEL ET AL 2007) |
| Sorting systems | (HOMPEL ET AL 2007) |
| Loading area | (GUDEHUS 2012) |
| Picking devices | (GUDEHUS 2012) |
| Transport materials | (GUDEHUS 2012) |
| Handling systems | (GUDEHUS 2012) |
| Internal communication | (NOFEN 2006) |
| Push production | (ROTHER & SHOOK 2009) |
| Pull production | (ROTHER & SHOOK 2009) |
| **Supply & Disposal** | |

| | |
|---|---|
| Emission control devices | (NOFEN 2006) |
| Disposal facilities | (NOFEN 2006) |
| Telecommunications | (NOFEN 2006) |
| Water supply | (NOFEN 2006) |
| Heat supply system | (NOFEN 2006) |
| Power installations | (NOFEN 2006) |
| Ventilation systems | (NOFEN 2006) |
| Extinguishing systems | (NOFEN 2006) |
| Energy & Media flow | (NOFEN 2006) |
| Outside facilities | (NOFEN 2006) |
| Vibration protection concept | (NOFEN 2006) |
| Heat and cold protection concept | (NOFEN 2006) |
| Sound insulation concept | (NOFEN 2006) |
| Fire protection systems | (NOFEN 2006) |
| Information flow | (SCHENK 2014) |
| **Assembly station** | |
| Provisioning | (NOFEN 2006) |
| Assembly process | (NOFEN 2006) |
| Output | (NOFEN 2006) |
| Tools | (HEINS 2010) |
| Finishing | (NOFEN 2006) |
| Layout/ Organization | (HEINS 2010) |
| Test/ Measurement equipment | (HEINS 2010) |
| Preparation area | (WIENDAHL ET AL. 2013) |
| Infrastructure/ building | (NOFEN 2006) |
| Furniture | (NOFEN 2006) |
| Automation | (NOFEN 2006) |

| | |
|---|---|
| Machines | (NOFEN 2006) |
| Lightning | (NOFEN 2006) |
| Safety devices | (NOFEN 2006) |
| Sensors | (SCHENK 2014) |
| Product parameters | (SCHENK 2014) |
| Load requirements | (SCHENK 2014) |
| Processing time | (SCHENK 2014) |
| Capacity | (SCHENK 2014) |
| Orders execution | (SCHENK 2014) |
| Assembly resources | (GÜNTHNER 2017) |
| Tools & jigs | (GÜNTHNER 2017) |
| Product | (GÜNTHNER 2017) |
| Subassemblies | (GÜNTHNER 2017) |
| Modules | (GÜNTHNER 2017) |
| Workforce | (GÜNTHNER 2017) |
| Painting | (HELBING 2010) |
| Welding | (HELBING 2010) |
| Cutting | (HELBING 2010) |
| Manufacturing processes elements | (SINGH 2010) |
| **IT Systems** | |
| Control systems | (SCHENK 2014) |
| Data acquisition | (SCHENK 2014) |

# IV USB Stick Content

0 – Digital version of the thesis

1 – Reference model evolution

2 – Validation model

3 – Figures

4 – Literature

# V Sworn Declaration

Ich erkläre hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt.

Garching, den 09.09.2019

(Luis Alcalá-Santaella Martínez)