UNIVERSITÀ
DEGLI STUDI
FIRENZE

DOTTORATO DI RICERCA IN
Ingegneria Industriale e dell’Affidabilità

CICLO XXX

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Toward a Lean Manufacturing Simulation Framework for the HVLV environment

Settore Scientifico Disciplinare ING-IND/17

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Anni 2014/2017

ABSTRACT

Lean manufacturing has been proven to be one of the best techniques to reach improvements in an ever-changing market context; it can be used to increase the performances in several branches of a manufacturing system reducing production time and costs. On the other side, the adoption of these paradigm can be difficult and can lead to problematic scenarios like an incorrect evaluation of the effort, both economical and time, for adopting it. Furthermore, many factories have an "high variety/low volume" (HVLV) manufacturing context and lean manufacturing has been based, and successfully used, with "Low variety/High volume" flow environments. The aim of this research is to provide an answer as to whether the adoption of a lean manufacturing system in a HVLV factory is possible and if it can lead to better overall performances. Modelling the existing manufacturing allows different cases, and approaches, to be simulated that can be applied to the manufacturing system. The results of simulations can suggest a better choice of methods and techniques of lean manufacturing to be applied reducing the risk of wasting time and resources.

Keywords: Lean Manufacturing, High-variety/Low-volume system, Conwip Simulation, Case study.

ACKNOWLEDGMENTS

Firstly, I would like to express my sincere gratitude to my tutor Professor Rinaldo Rinaldi for the continuous support of my PhD study and related research, for his patience, motivation, and deep knowledge in operational management. His guidance helped me in the whole research process and writing of this thesis.

Besides my advisor, I would like to thank Professor Romeo Bandinelli for its insightful comments and encouragement, but also for the hard questions which incentivized me to widen my research from various perspectives and providing me an opportunity to join their research team, giving me access to the laboratory and research facilities. Without their precious support it would not be possible to conduct this research.

Last but not least, I would like to thank my family and my closer friends for supporting me throughout the whole research and especially when writing this thesis.

Table of contents

Table of figures

Table of tables

Table of abbreviation

AS - Actual state
ATO - Assembly to order
BTO - Buy to order
CI - Continuous improvement
CNC - Computer numerical control machines
CODP - Customer order decoupling point
CWCard - CONWIP card
DOE - Design of Experiments
ETO - Engineer to order
FIFO - First-in First-out
FS - Future state
GT - Group technology
HRM - Human resource management
HVLV - High-variety/low volume
I4.0 - Industry 4.0
JIT - Just-in-time
KPI - Key performance indicator
LM - Lean manufacturing
LP - Lean production
LR - Literature review
LT - Lean thinking
LVHV - Low-variety/high volume
MTO - Make to order
MTS - Make to stock
MU - Mobile unit
NDA - Non-disclosure agreements

OKP - One-of-a-kind
OM - Operational management
PDCA - plan-do-check-act
PPC - Production planning and control
SC - Supply chain
SMED - Single minute exchange die
SMEs - Small and medium-sized enterprises
STS - Ship to stock
TPM - Total productive maintenance
TPS - Toyota Production System
TQC - Total Quality Control
TQM - Total quality management
TQM - Total quality management
VSM - Value stream map
WIP - Work-in-process

Outline of the thesis

In the first chapter an introduction of the PhD research will be given with a brief description of the topic that has been examined and developed during the whole research study.

The second chapter will state the foundations of the research deepening into the background of the most important topic shown in the first chapter.

Chapter three will analyse the methodology research used to conduct the studies and explain the reason of this choices.

Chapter four will focus on the case study that represent the most important topic that has been examined in this study.

Chapter five will illustrate the simulations related to the case study and the results obtained from the experiments; conclusion will follow comparing the research questions with the results reached.

1 - Introduction

The first chapter will introduce the main aspect of the work of this thesis. In the first paragraph, an industrial background will be given to introduce the topic and delineate the boundaries of the research and a brief explanation on why lean manufacturing is a key factor for competitiveness will follow. The identification of the market sector where the study is focusing on will be the content of next paragraph. Then both of the previous arguments will be examined together for getting an overview of the thoughts of the research. Subsequently the main research field will be analysed and the research objectives, questions and delimitation of the study will be illustrated.

1.1 - Industrial Background

In this paragraph a brief introduction to the industrial background will be given in order to understand which is the main topic that will be highlighted in the research, why it has been chosen and which is the domain of the study.

1.1.1 - Introduction

Nowadays lots of factors must be considered to achieve, and remain, a successful enterprise; the highly variable environment in which the companies are competing shows that factory processes, at every level of the hierarchy, has to be agile and reactive to sustain the company growth (Tyagi *et al.*, 2015). In a scenery with a strong international competitiveness, becoming more aggressive, small and medium enterprises (SMEs) must found solutions to increase competitiveness (Amaro, Graça; Hendry, Linda; Kingsman, 1999; Belekoukias, Garza-Reyes and Kumar, 2014). The smaller size of SMEs, compared to the larger ones, lead to evaluate carefully how to invest financial resources; outsourcing has been the answer for some of them, but many other companies have faced the problem and take it as a competition for renewing. Questioning about the production logic and the shift to a new paradigm means adopting a new production one called “Lean Manufacturing” (LM), or equivalent “Lean Production” (LP), as concrete result. LM helps to find and understand the customers’ needs to satisfy them in a direct and immediate way reducing at maximum the costs and utilizing resources, both material and immaterial, in the best way (Womack, Jones and Roos, 1990). The foundation of LM can be summarized in a productive system aimed at flexibility, simplicity and speed in creating value within the production process without losing the accuracy (Sohal and Egglestone, 1994; Dangayach and Deshmukh, 2001; Davies and Kochhar, 2002; Hallgren and Olhager, 2009; Vinodh and Joy, 2012;

Bortolotti, Boscari and Danese, 2015; Marodin *et al.*, 2015). Lean enterprises' goals can be defined as:

- Waste reduction
- Quality improvement
- Lead time reduction

LM involves the simultaneous application of several tools and techniques; as reported by (Shah and Ward, 2003), and their studies have identified the major four bundles of practices for LM:

- Just-in-time (JIT)
- Total quality management (TQM)
- Human resource management (HRM)
- Total productive maintenance (TPM)

These bundles represent a measurement scale of LM. Other fundamental principles like continuous improvement (CI) and the application of best practices like kanban, and other type of production progress, concur to maintain the competitiveness of the companies. Since the appearance of the book "The machine that changed the world" (Womack, Jones and Roos, 1990) became rapidly clear that being lean is mandatory to be competitive in the actual globalized market. Later, other authors (Sohal and Egglestone, 1994; Shah and Ward, 2003; Bortolotti, Boscari and Danese, 2015), gave the same results stating that LM is widely recognized as a philosophy aimed to improve the overall operational performance of a company.

1.1.2 - Production environment

LM arose from the automotive sector of Japanese market (Womack, Jones and Roos, 1990) that is defined "low-variety/high volume" (LVHV) meaning that the mix of articles produced are higher compared to the variety of product offered. On the other hand, not all companies belong to this production environment but they are competing in a specific one called "high-variety/low volume" (HVLV) in which the variety of articles is really high and the volume of articles produced is low. For clarity of the reader it must be said that in literature there is multiple, but similar, names for defining the HVLV environment like "high-variance/low-volume" or "high-mix/low-volume"; they are equivalent to the one used in this thesis. HVLV production environment could be a market's niche for companies competing in the field of luxury market like, e.g.:

- High Fashion industry
- Leather industry
- Jewellery industry

and many others; or more frequently HVLV companies are SMEs that, due to their size, have low volume and several clients to work with like third party supplier (Amaro, Graça; Hendry, Linda; Kingsman, 1999). For this reason, most of the tools applied in LM have been developed in an LVHV context and they are not applicable "as-is" in a HVLV context (Portioli-Staudacher and Tantardini, 2008) and the main focus of this research is about searching a solution to a better understanding if LM tools and techniques could be used in a HVLV company and if this leads to increase competitiveness.

1.1.3 - Italian production environment

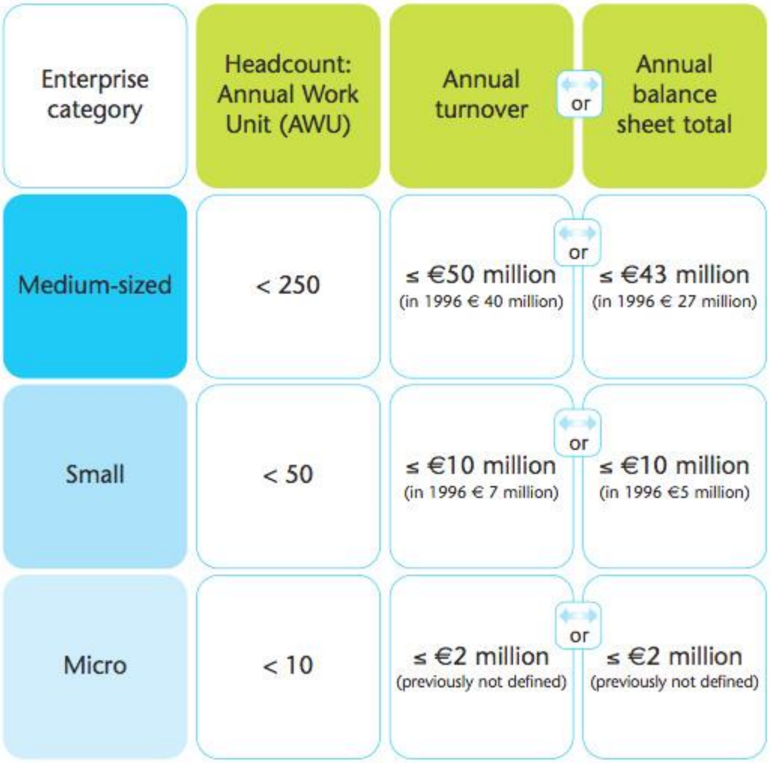
The context of this research is represented by the Italian manufacturing companies competing in a HVLV environment. Traditionally, Italian manufacturing market is largely dominated by SMEs that play a key role in the economy. Referring to added value quota, Italy is the seventh most industrialized country in the world and the second one in Europe after Germany (Giornale delle Pmi, 2017).

1.1.3.1 - SMEs definition

According to the European commission the definition of SMEs is fixed in the SMEs definition user guide (European Union, 2003) and the main factors representing SMEs are:

- Staff headcount
- Turnover
- Annual balance sheet

Figure 1 highlight the key role of staff headcount as one fixed parameter instead of turnover or annual balance sheet that can be evaluated separately. To be more precise the EU law stated "It is necessary to note that while it is compulsory to respect the staff headcount thresholds, an SME may choose to meet either the turnover or balance sheet ceiling. It does not need to satisfy both and may exceed one of them without losing its status" (European Union, 2003).



Enterprise category	Headcount: Annual Work Unit (AWU)	Annual turnover		Annual balance sheet total
Medium-sized	< 250	≤ €50 million (in 1996 € 40 million)	or	≤ €43 million (in 1996 € 27 million)
Small	< 50	≤ €10 million (in 1996 € 7 million)	or	≤ €10 million (in 1996 €5 million)
Micro	< 10	≤ €2 million (previously not defined)	or	≤ €2 million (previously not defined)

Figure 1 - SMEs definition (European Commision, 2015)

Considering the European Union, SMEs are the engine of the economy (European Commision, 2015); SMEs roughly represent nine of every ten companies and generate two jobs out of three. So, SMEs is a main target for the European Commission considering their importance regarding the economy of the whole Europe community; this is the reason why fixing a definition of SMEs became so important.

1.1.3.2 - Italian SMEs

The Italian industrial environment is basically composed by a large amount of SMEs (Table 1):

Type of companies	Number of companies
Small companies	4313163
Medium companies	21256
Big companies	3666

Table 1 - Italian manufacturing data (adapted from Istat)

A percentage representation of the Italian manufacturing data is reported in Figure 2:

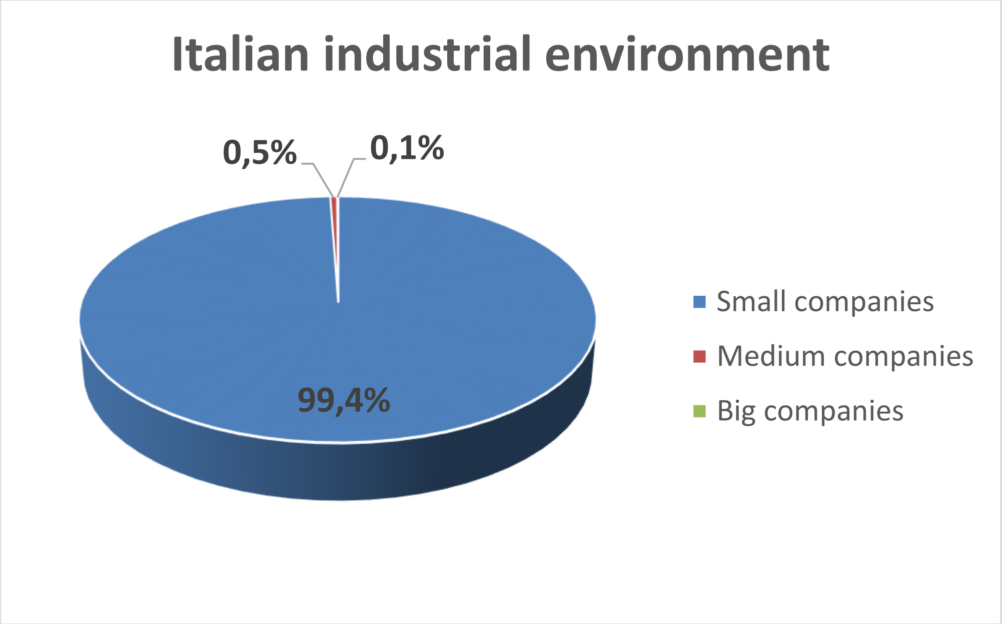


Figure 2 - Italian manufacturing data percentage

SMEs are the backbone of the Italian manufacturing system; job creation and economic growth are directly related to them and for this reason they must be evaluated carefully and helped to gain competitiveness.

1.2 - Manufacturing background

LM is a set of tools, methods and techniques that has been extensively studied in the academic field and a wide literature review is present (Bhamu and Sangwan, 2014). Nowadays, all the evidence point to the fact that LM is mandatory to increase the performance of a manufacturing company (Ohno, 1988; Womack, Jones and Roos, 1990; Womack and Jones, 1996; Hines, Holwe and Rich, 2004).

1.2.1 - A brief history of Lean Manufacturing

Starting from early 1970s Japan's economy was razed due to the oil crisis. In this context of high instability there was a company that starts to catch the attentions of the world: they were the Toyota motor company. The first approach of what will become LM was created by Taiichi Ohno around 1950. Taiichi Ohno with Kiichiro and Eiji Toyoda, owner of the company, went to U.S.A. to visit the Ford manufacturing plant. They soon realize that a typical mass production plant was not exportable in Japan due to many reasons:

- Difficulties of making big investment in technological machineries in postwar period
- Japanese market demand was driven by high variety of products and low volume of production
- Increased international competition

Due to the period of high economic instability, Ohno's first attempt was about modifying the plant's layout and put machinery in line of the production process and assign, to a single worker, more machines at the same time. Orders rose soon and Ohno sought immediately the necessities to introduce a sort of "leveled production"; with this term, we meant that the production is distributed in a regular manner within the working day to have a production flow constant and continuous. Dividing the monthly demand for the work's hours, it is possible to evaluate the number of pieces that should be produced every hour; to obtain a better performance and to meet the demands of the customers it is not sufficient to evaluate just the monthly production but it is also necessary to implement a series of interventions to the entire process of the supply chain (SC) to be able of sustaining a productive system lean-structured. The focus quickly moved from the inner company to the whole SC, including raw materials. The first goal that Toyota faced was removing any problem of technical, financial and labor force type to optimize the lead times and being free to focus on creating value. The foundation of the LM can be summarized in a productive system aimed at flexibility, simplicity and speed in creating value within the production process without losing the accuracy. Lean enterprises' goals can be defined as:

- Waste reduction
- Quality improvement
- Lead time reduction

Later a group of U.S. scientist discovered this new type of production system and they start to collect all the data to sum up the complete theory that later has been called LM. It has been exhaustively studied starting from the milestone "The machine that changed the world" (Womack and Jones, 1996). LM was inherently connected to the shop floor where it was born; in few years the philosophy of LM became more holistic and gained a managerial point of view; this evolution of LM has been called "Lean thinking" (LT) and explained in the homonymous book (Womack and Jones, 1996).

1.2.2 - A brief history of Lean Thinking

The way to shift from the old paradigm to the LM is LT and has five steps:

- Value
- The value Stream
- Flow
- Pull
- Perfection

1.2.2.1 - Value

Value is the fundamental starting point for LT; value can only be defined by the customers and has its reason to be when is fully expressed in terms of a specific attribute of a product which meets the customer's needs at a specific time and price. LT embraces this assumptions and Japanese executives of Toyota starts asking themselves where the value, for customers, lies and how to translate it into future products. When Womack started to travel the world to expand the idea of LT he soon realize that the concept of “value” was not completely understood (Womack and Jones, 1996). He found that most of the time the value of the product was not the one requested by the customer; the product was more sophisticated or simply not in-line with the customer needs and the question arose: who specified their value? The answer was the technician inside the company; engineers, executives and all the other roles were proud of the technologies contained in the product but, most of the time, the customer did not simply need it so they basically had no value. The Japanese vision of the value was: “value is where value is created” (Womack and Jones, 1996). To satisfy the customer needs, creating value for them, they start to ask themselves how to find which are the needs of the customer and, more precisely, where the value begins in the process of thinking, design and produce a new product. The answer they have found lead to the mindset of producing goods at home, with an eye to local needs. This definition of value is widely adopted because of the power of preexisting organizations and technologies plus an outdated thinking about economies of scale. The LT paradigm starts where this old mindset ends: precisely define value in terms of specific products that has specific capabilities offered at specific prices identifying the specific customers. Ignoring existing assets and technologies and creating a product-line basis with strong, dedicated product teams must be mandatory to remain competitive in the next years. Specifying value accurately is the most important step in LT and is the key to shift to a most performing industrial paradigm. After the value has been identified and so the product is defined the final element will be the target cost. Target cost is defined as the muda-free cost of the product and, once set, it will be used to evaluate every step in the value stream.

1.2.2.2 - The value stream

The value stream comprehends all the specific actions necessary to bring a specific product (a good or a service) through the three management tasks of any type of business:

- Problem-solving task
- Information management task
- Physical transformation task

The problem-solving task starts from the concept of the product through design and engineering ending with production launch; the information management task begins with taking the orders and gives a detailed scheduling for delivering the finished product. The physical transformation task goes from the raw materials to the finished product. Being able to identify the entire value stream for each product, or for each product family, is a step in which many companies normally fails. This can be a huge problem because this step lead to expose lots of muda. More specifically some of them will be identified as creating value; others will not create value but they are unavoidable due to technologies. Some of them will be found not necessary and with no value; these are type-two mudas.

1.2.2.3 - Flow

The first step to change is to find the value the customer needs and map the value stream for those specific product, or family of product. Consequently, most of the wasteful steps containing muda will be eliminated and therefore the entire process is ready for the next step that is making every step of the company flowing. As noted before, LT has been a disruptive way of thinking industrial processes; the common way of doing product, for example move it between departments, is the opposite of continuous flow. Flow thinking process is counterintuitive because for most people work should be organized by departments in batches. However, it is not possible to solve the problems dealing with disconnected processes instead of the entire flow of value. Most of the time some technical consultant try to reengineer the process in the departments but the change is often not understood and normally there is a regression when these facilitators are gone. The lean paradigm is about redefining the functions of department involved in the whole chain of value to understand that every step of the process is important for the value creation and it is their interests to make value flow between the chain value.

1.2.2.4 - Pull

Pull is the concept from where pull production has arisen; the simplified concept regards an upstream process that can not produce a good or a service until the customer demand, that control downstream process, asks for it. Real-word scenario is more complicated; sometimes the best practice to understand the logic is starting with a real customer's demand and work backwards through all the production steps. Using a pull approach will lead to gain an improved flow with a consequently reduction of time to market; reaching this goal will speed the delivery of products to the customer meaning that he can pull the product from you as needed in a very short time. A direct result of pull is that products don't need to be built in advance and there is no need to allow warehouse's space to stock both materials and semi-finished products. Inventory is one of the biggest muda that can be found in production system and can hides many other problems present; inventory is directly connected to occupied warehouses space and requires transporting. Adopting a pull logic production results in waste elimination thanks to lead time reduction and increased flexibility; the target is to produce just if there is a specific customer request. Customer demand used to be more stable in the past than today, both for quantity and complexity; economies of scale allowed high optimization through large batches production that is called mass production. Nowadays the market request is complex and diversified, in both quantity and variability. The key to maintain competitiveness in this high-complexity scenario is to make the customer pulling the company production flow; waste identification and elimination, in order to decrease ineffectiveness, has to go beyond the borders of the company and include all the suppliers in order to realize a strong collaboration along the whole SC.

1.2.2.5 - Perfection

Perfection is the fifth, and the last, point of LT and it involves the very simple idea of continuously improve to reduce effort, time, space, cost, and mistakes while offering a product which is close to what the customer actually wants (Womack and Jones, 1996). Once the new paradigm has been adopted in the company a virtuous circle starts between the other four principles; the flow of the process exposes hidden muda in the value stream so they can be removed. Furthermore, product teams in strict contact with customers' needs find new way to give more value to them. Kaikaku is a Japanese word that can be translated in radical change; it is relative to a fundamental and disruptive step done in a particular field (e.g. a production process). Kaizen is a Japanese word referred to continuous improvement; it is not as radical as kaikaku but it is a constant improvement to reach the perfection. Converting the classic batch-and-queue production system to continuous flow will result in kaikaku that will cut cost for the company and ensure a better response of the whole value of chain resulting in better profit of the company itself. Once LM has been adopted Kaizen will drive all the continuous improvement reducing muda and aiming to perfection. All those tools and techniques are so fundamental for the competitiveness of a company that the new revision of quality standards, ISO 9001, are based on the basic methods of LM.

1.3 - Manufacturing environment

The manufacturing environments related to the lean approach are essentially two:

- LVHV
- HVLV

1.3.1 - LVHV

The lean approach has born in the context of an automotive factory like Toyota, that is a big enterprise, and has low variety of products and a high volume of demand. LVHV manufacturing companies used to produce large quantities of goods and share the same concept of mass production: producing large quantities of goods in short periods of time. To summarize: LVHV constitute the commodity items for which there is typically a large and steady demand (Bhandwale and Kesavadas, 2008). Normally goods that are produced in LVHV are similar or with little, or no, differences. Companies use various processes to achieve high levels of output; assembly lines are high-volume manufacturing process where goods are assembled piece-by-piece by human workers, machines or a combination of the two. The main advantage is that high-volume manufacturing processes produce goods faster and reduce the overall cost of production per unit.

On the other side high-volume has some drawbacks:

- High costs of infrastructures
- High costs of equipment

LVHV production environment is best suited for product-focused process strategies.

1.3.2 - HVLV

SMEs engaged in HVLV manufacturing more likely operate as job-shop type of production (Amaro, Graça; Hendry, Linda; Kingsman, 1999) and tend to produce special order products for which the demand is typically unsteady (Bhandwale and Kesavadas, 2008). HVLV manufacturers must be both lean, meaning efficient and waste-free, and as flexible as possible. Being able to rapidly changeover their machines, work cells and support systems to produce a high variety of products is fundamental in order to be able to deliver goods by due dates to the customers. HVLV companies has no precise definition even though one that could be reasonable will be illustrated in the next paragraph. HVLV industries vary from airspace to fashion and, for example, it is really difficult to find analogy between these two types of business that, however, share the same manufacturing environment. HVLV presents these characteristics (Jina, Bhattacharya and Walton, 1997):

- Very high product variety
- Make-to-order policy
- Different level of vertical integration
- Varied processing lines

HVLV is a set of characteristics shared, independently of the business market, by all manufacturer. The sales process is complex and includes customer-driven design and configuration decisions. The products are highly configurable and the number of options and the configuration combinations are such that the demands for materials is difficult to be forecasted. As introduced before, SMEs faces many problems; starting from the fact that it is not possible to predict exactly if the enterprise will benefit from LM, if the improvement will have an affordable consulting cost comparing to the obtained results and if those improvements are aligned with the strategic enterprise goals (Slomp, Bokhorst and Germs, 2009; Cortes *et al.*, 2016). Furthermore, the major problem is relative to the demand; in SMEs, and especially in the ones who had their business in a market's niche, is very common to have lower volume per orders even reaching the one-of-a-kind (OKP). As stated in the previous paragraph these can lead to a problematic choice of which of the usual techniques of LM can be used. After an in-depth analysis of literature (Cortes *et al.*, 2016) has found that main problems are relative to:

- Lack of data collection with low reliability
- Lack of continuous real time collection
- Performance target mismatch between different manufacturing levels

One of the crucial parameter to identify is key performance indicator (KPI); these values can be compared to the goals we want to achieve and gives us important information about the application of LM in the processes. There are many types of KPIs and they have to be selected to measure the performance related to the company's strategic goals and in particular they have to be tailored for competing in the environment where the company operates. Identifying the wrong KPIs, starting from a wrong vision of the company, can lead to collect useless data and furthermore takes decision on the wrong set of information. Some of the most useful and most generic KPIs are related to these aspects: financial, technical and efficiency. Normally, they are based in the short period and they have to be continually calculated and reviewed (Ahmad and Dhafr, 2002). The most generic strategy KPIs can be divided in 5 categories (Corbett, 1998):

- Cost
- Quality
- Flexibility
- Stock
- Lead times

After the choices of the right KPIs they need to be evaluated as a whole; considering the results of just one, or few more, KPIs is not sufficient to establish the system's performance. Normally, in the short time period, using KPIs will lead in company's better performances; however, decisions can't only be based on the raw value of numbers and percentage because, on long term, these can result in reduced performance. What it has to be defined is the leanness of the enterprise's processes; by leanness we mean the degree of adoption of lean philosophy in an organization. Some of the most used methods are (Cortes *et al.*, 2016):

- Interviews and surveys
- Benchmarking
- Fuzzy models

Every type of this method has its pros and cons but they don't consider, at various level, the dependencies between different indicators. To evaluate the leanness in a correct way a bigger picture is necessary; it has to be found a holistic approach that will link together KPIs, leanness (meaning methods and techniques) and company's vision.

1.4 – Application of Lean Manufacturing in HVLV

Even though a great number of papers, articles and books are available for LM, applications of LM in a HVLV context is scarce in the literature (Bhandwale and Kesavadas, 2008; Veldman and Klingenberg, 2009; Buetfering *et al.*, 2016); an in-depth analysis of this statement will be examined in the next chapter. However, HVLV manufacturing systems must keep high performances while being agile and flexible to face the ever changing environment and the increasing uncertainty of the customer demand (Tyagi *et al.*, 2015). Implementing LM principles has been proven to be an effective approach in seeking operational excellence (Slomp, Bokhorst and Germs, 2009). Unfortunately, not all the standard methods and techniques, the one used in LHVH environment, are applicable in HVLV environment (Portioli-Staudacher and Tantardini, 2008). However, for both environments, uunderstanding the source and reducing at maximum the variability remains one of the key concepts in lean transformation. LM principles are used to improve the overall performances of the company acting on these three main subjects:

- Production levelling
- Pull system
- Takt time, or equivalent, control

Levelling the production consist in reducing the variability acting on the manufacturing process and allow to maintain a stable flow of material through the shop floor. A fundamental point in lean approach is adopting a production pull-system; Hopp and Spearman (2004) gave this definition: “A pull production system is one that explicitly limits the amount of work in process that can be in the system”. The last point is about setting a control time, a pace time who helps to understand which is the right amount of production referred to the customer' demand. As can be seen these tools works together; in fact, levelling the production will result in smoothing the flow of materials in the production's cell while the work in process is kept constant and the overall production's rate is defined exactly to meet the right pace. Besides all the results that the usage of these tools can lead to, the challenge of introducing Lean in HVLV production environments is difficult to overcome (Portioli-Staudacher and Tantardini, 2008). For example, the mentioned production levelling and the pull system, mostly Kanban, were specifically designed for repetitive production environments; discussing the integration and implementation of new LM production control principles in HVLV companies are still few and far (Bokhorst and Slomp, 2010). HVLV companies faces many challenges compared to LVHV companies that are normally big companies with more financial resources; they have to react to turbulent environments and this turbulence lead to a difficult production's schedule and a complex materials' management caused by the frequent changes of customer' orders that however must be shipped with high quality, especially for luxury sector, with always shorter delivery times. That is why so many companies choose to adopt the LM principles: the only way to guarantee a reasonable delivery times with a good level service is to reduce the lead times of the processes and get a stable production plan even with a turbulent and ever-changing customer's needs.

1.5 -Objective, research questions and delimitations

The previous chapters stated that applying LM principles to company is mandatory to gain the necessary competitiveness to successfully being in the market (Womack, Jones and Roos, 1990; Amaro, Graça; Hendry, Linda; Kingsman, 1999; Belekoukias, Garza-Reyes and Kumar, 2014; Tyagi *et al.*, 2015). Some problems arise when the manufacturing environment is HVLV due to the fact that same of the LM tools and methods can not be applied with a straight-forward approach or even can not be applied at all (Portioli-Staudacher and Tantardini, 2008). Moreover, HVLV companies are normally SMEs (Jina, Bhattacharya and Walton, 1997; Amaro, Graça; Hendry, Linda; Kingsman, 1999) that have less financial resources to be employed in operational management (OM) and it must be pondered wisely. The uncertainty of adopting LM principles, investing time and money, that could not increase performance or even could not work at all is a strong resistance in the application of LM principles in HVLV companies (Achanga *et al.*, 2006; Bhasin and Burcher, 2006; Marek *et al.*, 2007) even though (Boyle and Scherrer-Rathje, 2009) asserted that the LM implementation can mitigate this possible effects. Still, the need of LM adoption remains and the purpose of the research of this work is how to help HVLV companies to understand if the LM adoption is feasible for the specific company and on which extent the performance will be improved.

1.5.1 - Objective

As mentioned above, the objective of this PhD research is to help HVLV companies to understand if implementing LM principles is a good trade-off between invested financial resources and improved manufacturing performances. In order to achieve the results, a low-cost solution and high-effective tool must be found (Detty and Yingling, 2000; Slomp, Bokhorst and Germs, 2009; Cortes *et al.*, 2016); simulating a customized and detail-rich HVLV environment for testing LM tools through a simulation software is the most effective way to reach the objective. The execution of simulations will be described precisely in the next paragraphs. The improvement obtained, if any will be reached, will be analyzed through the adoption of specific KPI commonly used in literature (Shah and Ward, 2003; Rother and Shook, 2009) like:

- Work-in-process (WIP)
- Resources Utilization
- Cycle Time
- Lead Time
- Advances and Delays

WIP is a production and SC management word to describe partially-finished goods awaiting to be complete. WIP refers to the raw materials, labour and other related costs needed for products manufacturing that are at various stages of the production process. Resource utilization represent the working time, or percentage, of machines employed in the production lines. Cycle time represent the period of time required to complete one cycle of an operation while lead time is the latency between the start and the end of a process. Lastly, advances and delays compares the dates of current deliveries with the requested ones. As pointed before, as this tool aspire to become a LM simulation framework for the HVLV environment so the simulation model is a detailed replica of an Italian HVLV company competing in the fashion industry. The single case study research has been selected for its adherence to the theoretical background and research question (Yin, 2009). In particular, the company selection was done considering its complexity and its representative characteristics of the industrial segment under examination; these peculiar characteristics make us think that it will be possible to make generalized statements from the obtained results. The most important data, like production time, workers, work shifts, etc., are the ones gathered from the company in order to obtain the most realistic results. The company will be named Alpha due to the fact that most of the disclosed information is confidential.

1.5.2 – Research questions

The research of this PhD thesis addresses the following research questions:

- Are LM tools applicable in a HVLV environment?
- Which and how LM tools can be applied in HVLV environment?
- What are the advantages of LM in a HVLV environment?

1.5.2.1 - Are LM tools applicable in an HVLV environment?

The wide literature available on LM and its implementation in companies is strictly connected to LVHV manufacturing environments and commonly related to big companies. For this reason, all the tools, techniques and methodologies currently evaluated were designed for that specific manufacturing line. The first question refers to the investigation of the applicability of such tools to a different manufacturing domain, like HVLV. An extended analysis of the current state of art of application of LM tools to HVLV will be illustrated in chapter 2.

1.5.2.2 - Which and how LM tools can be applied in HVLV environment?

The second question is an extension of the first one; if the research point out in the direction that LM tools are applicable in HVLV environment an accurate literature review will identify which LM tools, methods or methodology have the best performances and how they can be applied. After this research that will be deepen in chapter 3, and based on evidence, a LM tools that has been considered applicable to HVLV will be simulated through software in an industrial case study in order to validate the assumption and analyse the performance obtained.

1.5.2.3 - What are the advantages of LM in an HVLV environment?

One of the most important way to improve the production system is to identify and reduce at its best the variability. To do so production levelling is fundamental to gain a stable and constant flow of materials through the shop floor (Slomp, Bokhorst and Germs, 2009). Introducing pull systems that are able to limit the WIP is also a key factor (Hopp and Spearman, 2004). Kanban is the most used tool in LVHV environment (White and Prybutok, 2001) to achieve these results but it can not be implemented in LVHV (Staudacher and Tantardini, 2012).CONWIP (Spearman, Woodruff and Hopp, 1990) is one of simplest tools that can be utilized to replace Kanban and the easiness of implementation in HVLV environment is one of its most important quality. Creating a model of the enterprise at the actual state (AS) is the ground zero of the study; validating this state and simulate the future state (FS) will give information about the feasibility of investing time and money on adopting LM in the enterprise.

1.5.3 - Delimitations

The study presented is mainly focused on the research for helping the HVLV companies to understand the feasibility of adopting a lean approach using a simulation software. As stated before, normally HVLV companies are SMEs (Jina, Bhattacharya and Walton, 1997) and the Italian production system is highly represented by those types of industry; therefore, if the research will lead to shows some good results, the author's expectation is that this will lead to an adoption of the framework by other Italian HVLV's companies, besides Alpha, in order to increase the competitiveness and give a practical outlook at this thesis.

2 - Background

This chapter will focus on building a solid foundation for the thesis work. The first paragraph will analyse the literature review regarding the topics introduced in the first chapter and the following paragraphs will deepen the knowledge of the main concepts present in the literature.

2.1 - Literature review

As suggested by (Flynn, 1990), the literature review (LR) that has been accomplished for this work aim to establish a solid theoretical foundation for the PhD research and three main components has been evaluated:

- Search engines
- Research keywords
- References overview

2.1.1 – Search engines

Lots of scientific search engines are available nowadays that collect the widest knowledge in the most important scientific branches; for the industrial engineering sector the most important ones are (Table 2):

Search engine	Publisher
Scopus	Elsevier
Science Direct	Elsevier

Table 2 – Search engines

Google scholar, a relatively new search engine, deserves a special mention for the wideness of the results that can be obtained. In itself, this feature is both good and worse; good because it gives a huge number of results and allow to find something interesting but worse because it can be very time consuming. However, google scholar is still in development and the search results are, at today, not good enough as the ones obtained by the search engines reported in Table 2.

2.1.2 – Research keywords

As discussed in the introduction and for clarity of the reader, some of the keywords used for the LR are used in equivalent way to describe the same topic; for example, as in Table 3, "HVLV" identify all the results obtained by the concatenation of all the keywords that are reported in parenthesis in order to cover as much as possible the knowledge domain of the specific topic. The keyword used for the LR are:

Keywords
HVLV (high-variety, high-variance, high-mix, low-volume)
Lean manufacturing (lean manufacturing, lean production)
CONWIP
Simulations
Case study

Table 3 - Keywords

The whole LR is related to at least one of the main topics connected to the keywords illustrated in Table 3. Figure 3 represents the percentages of this relationship:

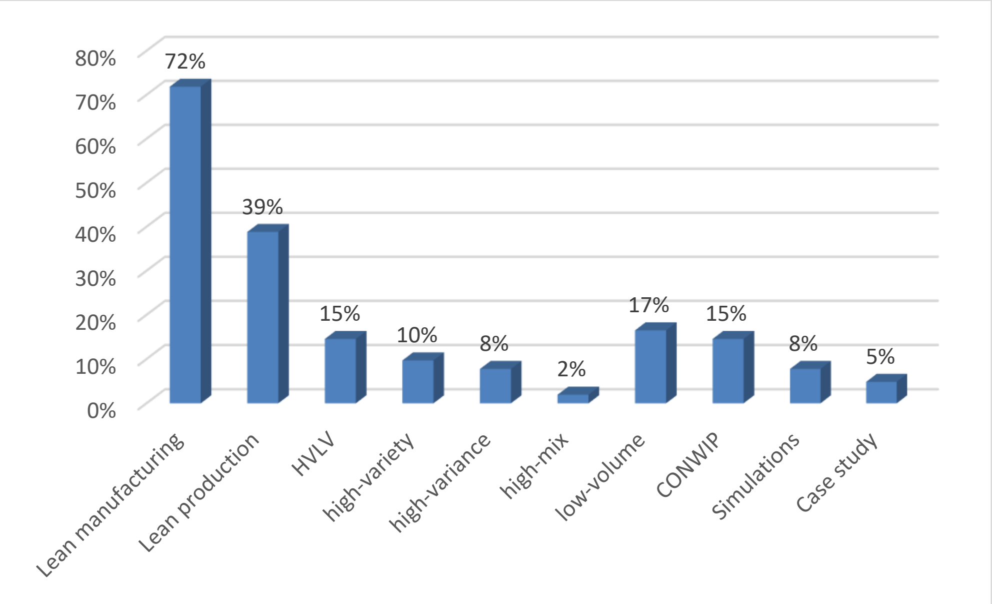


Figure 3 – Keywords related to LR

2.1.3 - References overview

The LR will deepen the established scientific knowledge that has been found using the most important keyword related to this field of research. Then, quoted references will be illustrated with the purpose to support the citation available in the whole thesis. The quoted documents used for this dissertation are illustrated in Table 4:

Reference type	#	%
Journal paper	79	77%
Book	20	19%
Conference proceedings	3	3%
Web pages	1	1%
Total reference amount	103	

Table 4 - Reference type

A graphical representation of the reference type quoted in the research can be seen in Figure 4:

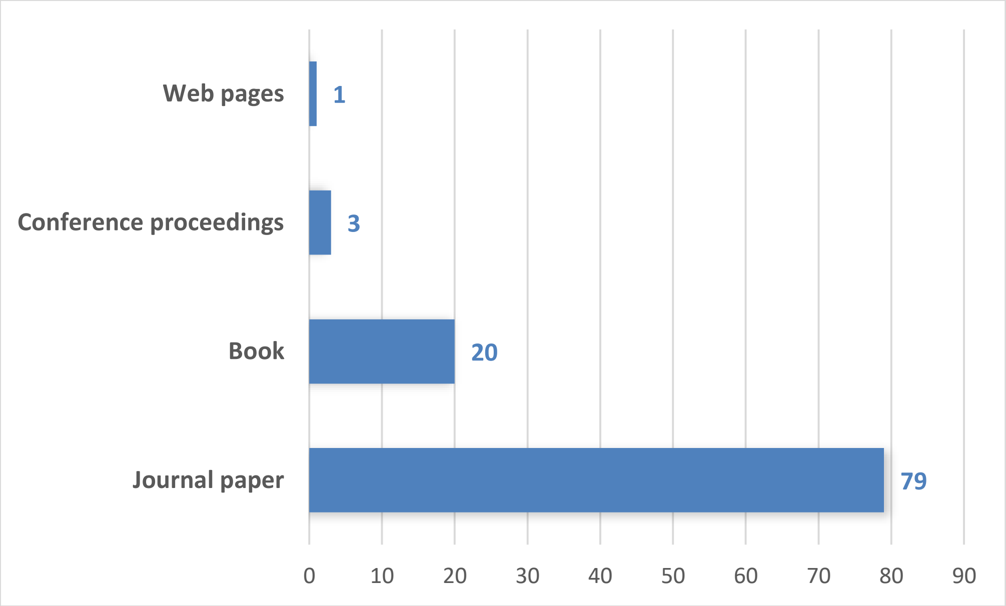


Figure 4 – Reference type percentage

As reported in Table 5, almost half of the articles quoted have been published in one of this most important Journals:

Name of the Journal	Number of papers
International Journal of Production Research	16
International Journal of Operations and Production Management	11
International Journal of Production Economics	9
Journal of Operations Management	5
Journal of Manufacturing Technology Management	3
Production Planning and Control	3

Table 5 – Most important Journal

A graphical representation of the whole documents quoted in the study work is highlighted in Figure 5:

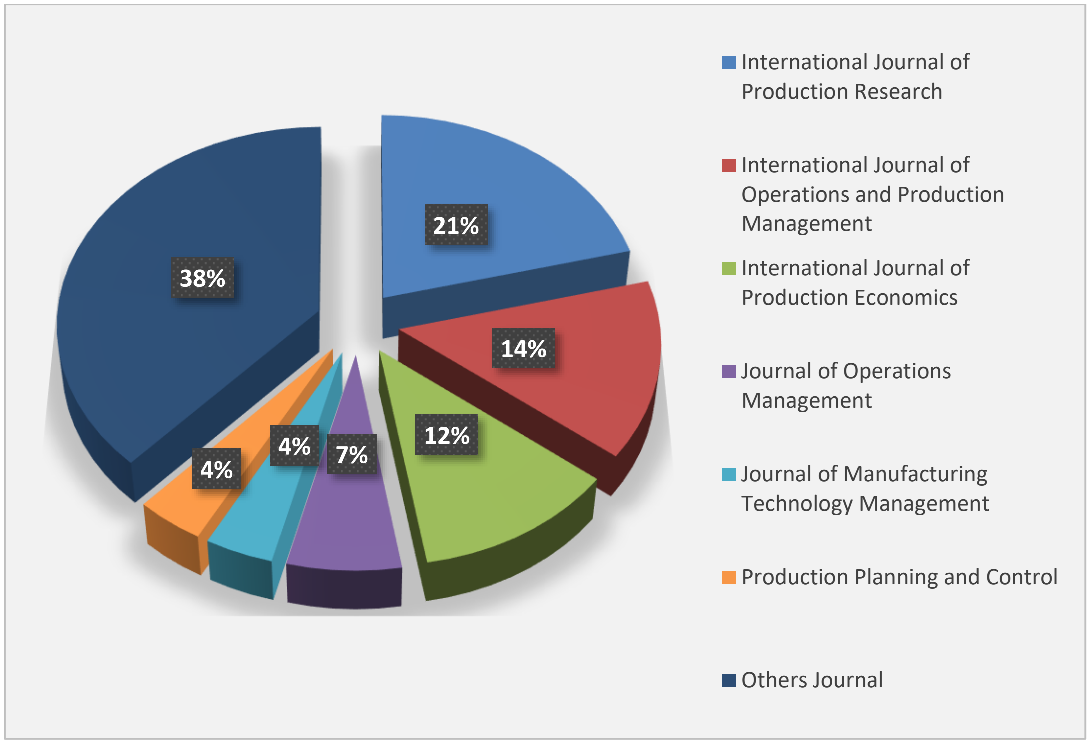


Figure 5 - LR documents

2.2– Lean Manufacturing

Japanese people get serious damages after the second world war; cities and factories were almost razed and they had shortages of every type of resources, especially human ones and raw materials. Besides, the US industry, especially the automotive sector, were producing at full pace with a factor of approximately 10. The management of Toyota respond with a brand-new philosophy in production aimed to reduce constantly the wastes, called "muda" in Japanese, of the processes. This lean approach, born in the Toyota factory, has been the main reason on why Toyota became, on long term, the biggest automotive company in the world. The main principle of the lean approach is to find and reduce the wastes in the production lines; Ohno has identified 3 types of wastes (Ohno, 1998):

- Muda
- Muri
- Mura

2.2.1 - Muda

Muda are defined as the tasks with no added value and is the key concept of the entire lean philosophy; muda can be also described as something that destroy value. There are two types of muda:

- Muda type I
- Muda type II

Muda type I is the one that occurs when the resources are used for an operation which does not create direct value for the consumer but it is necessary to produce the goods. Muda type II is not generating any value, directly or indirectly, and must be eliminated. Statistically in a factory there are 7 types of Muda:

- Overproduction
- Wait
- Transportation
- Stock
- Unnecessary activity
- Defects
- Motion

2.2.1.1 - Overproduction

Overproduction has always been considered the most important one and it must be limited in a very aggressive way to avoid stock's accumulation (Ohno, 1998). Producing more parts than those actually required by the customer' demand will lead to use unnecessary materials, human resources and company's space.

2.2.1.2 - Wait

When a worker is waiting, for example from a supplier or from the warehouse, the necessary material to perform his work the production flow stops.

2.2.1.3 - Transportation

Moving products increase the risk of damage, loss and delays and this activity is not value-added. These types of problem occur in these scenarios:

- Lack of optimization of internal logistics
- The layout of the production facility was not designed properly and not optimized for the production process
- The spaces occupied by the production lines are excessive

2.2.1.4 - Stock

The raw materials and the finished products exceeding the demand and stocked are wastes in terms of space and financial resources. The material in the warehouse is not creating value and can became rapidly obsolete with risks of damages for stock and handling.

2.2.1.5 - Unnecessary activity

This waste happens inside a production process when there is an unnecessary use of resources, for example machinery and employees. It may happen that the type of systems used for production has a greater capacity than what is required or that a qualified operator performs a task that could be done by an automatic machinery; in such case there is an underutilization of resources.

2.2.1.6 - Defects

The non-compliance of products involves waste of time and financial assets as well as problems with brand reputation: the production slows due to the rework and the lead time increases. Therefore, costs for repairing the correct product arise.

2.2.1.7 - Motion

The movement's muda is related to people and machinery; all movements not value-added are considered connected to the incorrect layout of the plant and the work stations.

2.2.2 - Muri

Muri identifies the surcharges; for example, the waste from overload, resources and people. The overload of machinery's work may lead to increase the possibility of breakings and a subsequent stop for repair. For human resources, excessive efforts of the duties may result in short term accidents and in the long term can increase the chance of work-related diseases.

2.2.3 - Mura

The expression Mura refers to the waste of unevenness; irregularities of the demand can generate periods of Muri alternated with periods in which the resources are under used, e.g. the workforce and machinery. In this situation, the flow is unstable and the production must be levelled; this is called heijunka.

2.2.4 - Heijunka

Heijunka is a method for balancing the production to avoid peaks and even the work load; key elements of heijunka are:

- Production's volume levelling
- Production's mix levelling

This is perhaps the most counterintuitive tools used in LM and consists in:

- Reducing production lots
- Keep constant the total product volume

Production lots must be reduced to the minimum term even if there was a possibility of demand aggregation. In a perfect pull system each product would require a dedicated line, an independent planning and a constant production. Realistically, more codes are produced on the same line, involving different cycles, different equipment, dedicated materials. The advantages of this system can be summarized as follows:

- Delivery times
- Warehouse
- Upstream resources
- Customer demand peaks
- Special work centers
- Raw material shortage

Heijunka uses small batches and a balanced distribution over the production process and does not favor any article so they all tend to have the same lead time; the small batches are consumed in a short period of time and replenished by other small batches, only if necessary. Warehouses are low or does not exist. Small batches require little material so the distribution is facilitated to replenish; commonly the supermarket is low and proportional to the average consumption. The levelling of product mix allows in the short period to react fast to sudden needs; if the increased demand will remain constant it is necessary to review the production capacity of the line. The levelling offers two major advantages to work centers: they gain a constant activity and the needed capacity is sized to real needs.

Having a material shortage involve only particular article; the other ones are normally produced by modifying the sequence of production; when the material is replenished production process is resumed. Heijunka at its best will need severe requirements:

- Time to setup
- Flexibility
- Quality
- Supplies

Due to the high number of small batches the setup time required must be minimum, under ten minutes; standardization of the production phases is important to maintain the setup time constant. Operators and machines must be capable of doing various tasks; operators ready to operate on multiple stations avoids bottlenecks. However extreme flexibility of the operators can lead to quality problems. Problems checking, poka yoke and the possibility to stop the production lines are essential. Reaching a fixed percentage of non-quality stops in the upstream process lead to a production line stop that is more convenient than the proliferation of problems in the downstream process. The simultaneous production of a great variety of products need a wide availability of material. Deliveries must be synchronized to arrive at the time of requirements and never in large batches. To guarantee the result the production process must be very flexible; on the contrary mass production causes all the types of wastes: muda, muri e mura. As we have seen the flexibility of lean production allows to produce low volume of orders and, even though levelling a low volume production is a hard job, is necessary to find always new production solution and never stop experimenting. Furthermore, levelling the production means less stocks and better reactivity to customers' needs leading to an overall better performance.

2.2.5 - Takt time

Takt time is defined as:

$$Takt\ time = \frac{\text{Available production time}}{\text{Customer demand}}$$

It sets the pace at which the production flows and it is used to check if the process is on time or it has some delay.

2.2.6 - Flow time

Flow time can be defined as:

$$Flow\ time = \frac{WIP}{Throughput}$$

or, alternatively:

$$Flow\ time = Takt\ time * WIP$$

2.2.7 - Standardized work

Standardized work is needed to establish precise procedures for the operator that is working in the production process and it is based on three elements:

- Takt time

- The work sequences
- The standard inventory

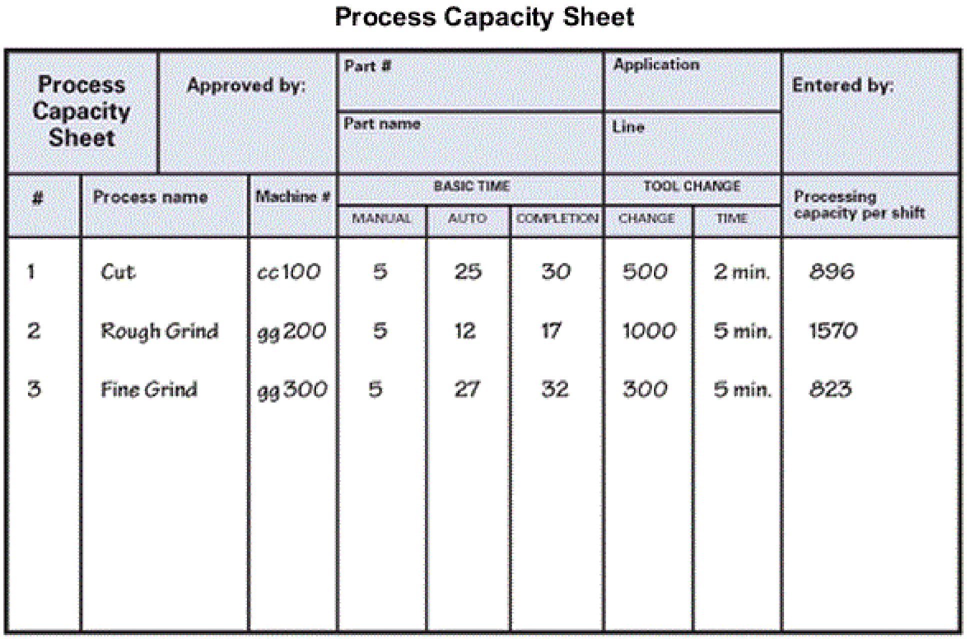
The work sequences are referred to the schedule in which an operator performs several tasks within takt time. The standard inventory is required to keep the process flowing smoothly and includes units in machines. Standardized work are tasks that has to be established by a team and displayed at workstations; Kaizen will drive the continuous improvement. The main benefits of standardized work are:

- Reduced variability
- Documentation of the current processes for all shifts
- Easier training of new operators
- Reductions in injuries and work-related disease
- Continuous improvement-driven process

Three basic forms are commonly utilized for creating standardized work. These are used by engineers and front-line supervisors to design the process and by operators to make improvements in their own jobs. They are:

- Process capacity sheet
- Standard work combination table
- Standard work chart

Process capacity sheet (Figure 6) is used to calculate the capacity of each machine in processes linked together. The goal is to confirm the true capacity for identifying and eliminate bottlenecks. This sheet is useful to determine factors like machine cycle times, tool setup and change intervals, and manual work times.



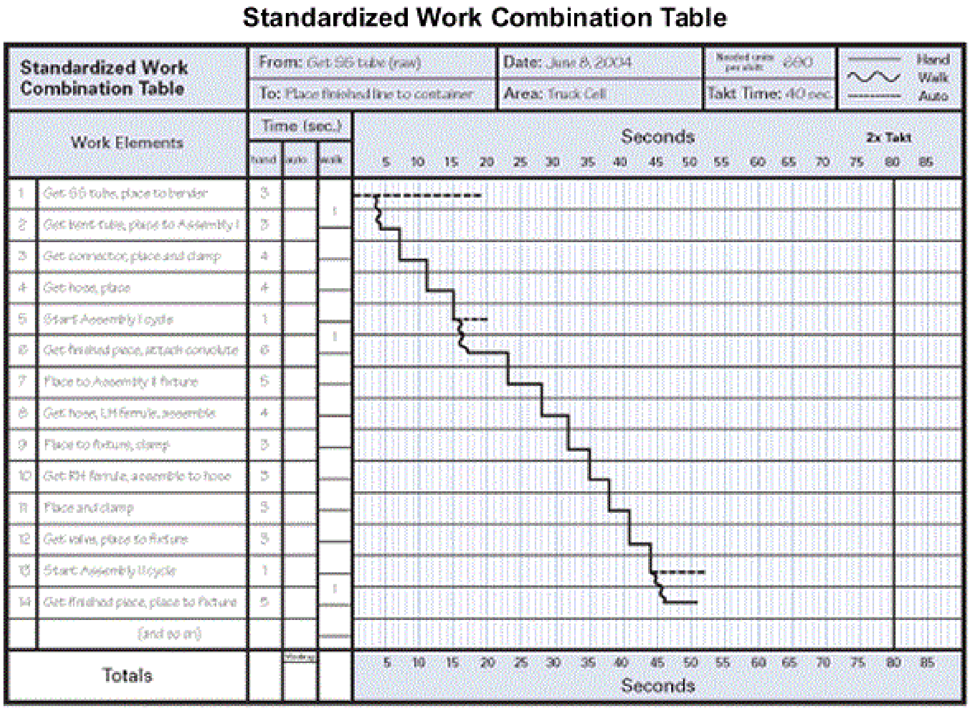
Process Capacity Sheet

Process Capacity Sheet	**Approved by:**	**Part #**	**Application**	**Entered by:**
		Part name	**Line**	

#	Process name	Machine #	BASIC TIME			TOOL CHANGE		Processing capacity per shift
			MANUAL	AUTO	COMPLETION	CHANGE	TIME	
1	Cut	cc100	5	25	30	500	2 min.	896
2	Rough Grind	gg200	5	12	17	1000	5 min.	1570
3	Fine Grind	gg300	5	27	32	300	5 min.	823

Figure 6 - Process capacity sheet (Lean Enterprise Institute, 2012b)

Standard work combination table (Figure 7) shows the impact of manual work time, walk time and machine processing time done by each operator in a production sequence. The table shows how operators and machines interact in a process and allow to set dynamically the operator work content as takt time expands and contracts over time.



Standardized Work Combination Table

Standardized Work Combination Table	From: Get SS tube (raw)	Date: June 8, 2004	Needed units per shift: 690	Hand Walk Auto
	To: Place finished line to container	Area: Truck Cell	Takt Time: 40 sec.	

	Work Elements	Time (sec.) hand	auto	walk
1	Get SS tube, place to bender	3		1
2	Get bent tube, place to Assembly I	3		
3	Get connector, place and clamp	4		
4	Get hose, place	4		
5	Start Assembly I cycle	1		1
6	Get finished piece, attach convolute	6		
7	Place to Assembly II fixture	5		
8	Get hose, LH ferrule, assemble	4		
9	Place to fixture, clamp	3		
10	Get RH ferrule, assemble to hose	3		
11	Place and clamp	3		
12	Get valve, place to fixture	3		
13	Start Assembly II cycle	1		1
14	Get finished piece, place to fixture	5		
	(and so on)			
	Totals			

Figure 7- Standard work combination table (Lean Enterprise Institute, 2012b)

Standard work chart (Figure 8) shows operator movement and material location related to the operating machine and the overall process layout. The chart shows the key elements that constitute standardized work:

- Current takt time
- Current cycle time
- Work sequence
- The amount of required stock

Standard work charts must be visible in the workstations' place as a tool for visual management and kaizen; as the demand vary they need to be updated and a continuous review in necessary to improve the performance.

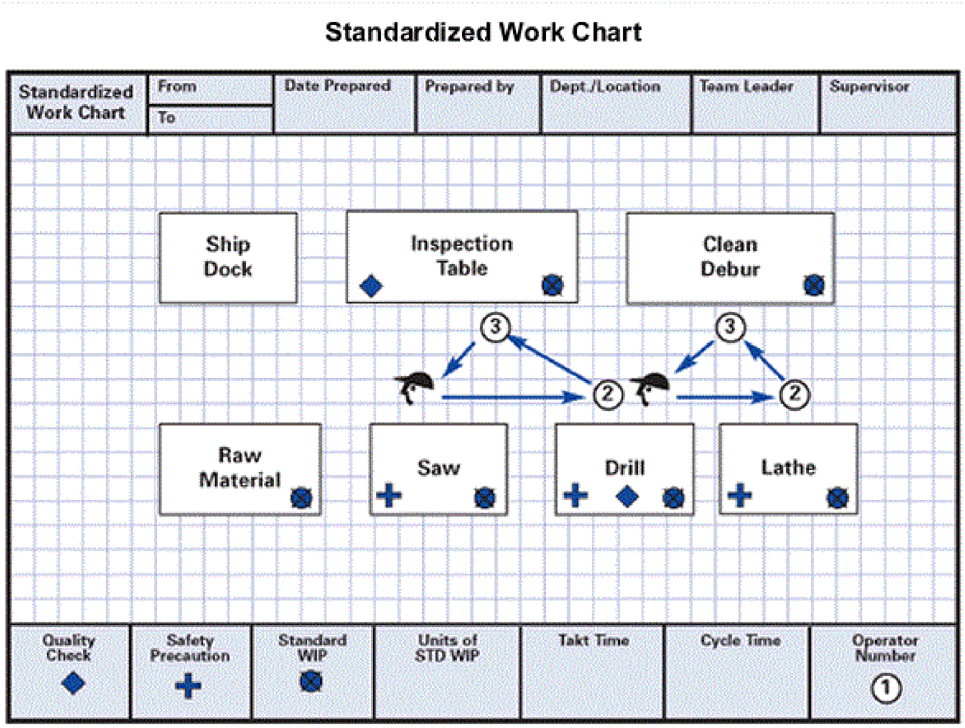
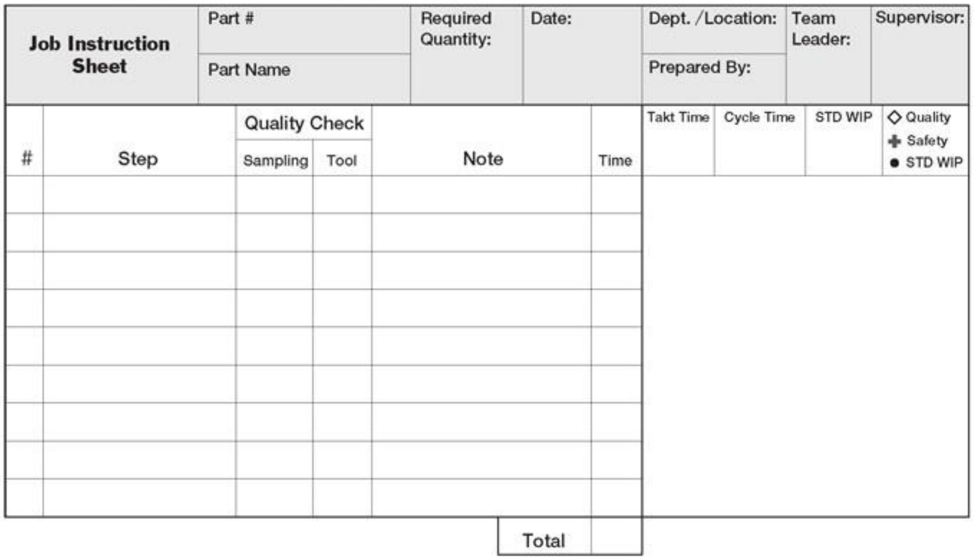


Figure 8 - Standard work chart (Lean Enterprise Institute, 2012b)

Standard work tools are used in conjunction with two other sheets:

- The work standards sheet
- The job instruction sheet

The work standards sheet is composed by a variety of documents that define how to build the product according to the engineering process; the work standards sheet details precise operational requirements that must be followed in order to assure product quality. The job instruction sheet (Figure 9) is used for the training of new operators. The sheet lists the steps of the job highlighting any detail that may be required to perform the job safely with utmost quality and efficiency.



Job Instruction Sheet	Part # Part Name	Required Quantity:	Date:	Dept. /Location: Prepared By:	Team Leader:	Supervisor:

#	Step	Quality Check		Note	Time	Takt Time	Cycle Time	STD WIP	◇ Quality ✚ Safety ● STD WIP
		Sampling	Tool						
				Total					

Figure 9 – Job instruction sheet (Lean Enterprise Institute, 2012c)

2.2.8 - Kaizen

Kaizen is a Japanese word composed by two terms; "Kai" means change, improvement and "zen" means better, good. Kaizen can be seen as a good change through a continuous improvement and can be referred as:

- System, or flow, kaizen
- Process kaizen

The first one is aimed to the management level of the company; it is focused on the overall value stream and is used to get a wider view of the company processes. The second one is focused on individual processes and referred to team leaders with work teams.

2.2.9 - Lead time, cycle time and work in process

Lead time is formerly defined as is the amount of time that elapses from the order's receiving to its delivery. Reducing lead time is one of the primary goal for enterprises and it must not be confused with the cycle time that is the period required to complete one cycle of an operation. Cycle time is relative only to the progress of product so it's product-related; lead time is what is seen by the customer. Lead time normally can be affected by some delays:

- Lot delays
- Process delays

These delays, that are muda, can be reduced by observing WIP that is used with articles that are not raw materials nor finished product and can be calculated as:

$$WIP = \frac{Lead\ time}{Cycle\ time}$$

In LT, WIP is the indicator of wastes caused by bottlenecks in productions process.

2.2.10 - Poka Yoke

The progress in machinery's technology has increased productivity and consequently, in the event of machine failure, the number of defective parts may be very high. To avoid unnecessary costs Toyota introduced machines capable of preventing in autonomous way the drawbacks in the production. This is done through the adoption of a device capable of identifying the problems during the production process, i.e. the defects, and stop automatically the production preventing to produce wrong articles. This type of control is named Poka Yoke and can be translated in error-proof. Later Poka Yoke has been used extensively in the whole enterprise; for example, Poka Yoke design is related to engineering pieces that can be assembled only in one way to avoid the operator error.

2.2.11 - Jidoka

Jidoka can be translated in autonomation that means automation with human intelligence; it is the ability of machine and operators to detect when an abnormal condition has occurred and immediately stop work; this lead to operations aimed to increase quality at each process and to separate men and machines for more efficient work. Jidoka is considered one of the two pillars of the lean house (Figure 10) on which the Toyota Production System (TPS) is found. Jidoka directly affects the organization of work along the production process; the machine does not normally require operators and human intervention is necessary only if there are faulty conditions. The workers can dedicate themselves to different working-places at the same time with a consequent reduction in the number of workers and an increase in production efficiency. TPS is a methodology based on the research of wastes; it is influencing every organizational aspect and comprehend a series of values, knowledge and procedures. Employees are working with responsibilities for each step of the process and are encouraged to improve the way of working if they see the possibility; the consequence is that the organization, in a holistic view, improves the overall performance.

Figure 10 – The Lean house (Rosing, Scheel and Scheer, 2014)

The benefits of a lean organization vary from the reduction of time needed to produce the products and the better overall quality of the whole value chain. However, the lean philosophy must be considered as a multi-dimensional approach; using all the tools and techniques provided by LM in a mechanical approach is not correct. The winning strategy is related to select the right tools to reach the desired goal and test continuously the usefulness of these tools.

2.2.12 - Just in time

Just in time (JIT) is the backbone of the whole lean process and is the other pillar of TPS; the main objective of JIT is the continuous elimination of all types of muda (Sugimori *et al.*, 1977). It ensures that suppliers deliver the right quantity at the right time in the right place (Shah and Ward, 2007); when the customer demand shows up these one is transmitted backwards from the finished product to raw materials. The result is a pull process in which the items are produced just when they are requested. A strong partnership between the company and suppliers are a key factor for success (Ansari and Modarress, 1988; Prajogo and Olhager, 2012). Using this method will reduce warehouse stocking of raw material and semi-finished products and operating costs.

2.2.13 - Production logic

Production logic refers on how the products are designed and manufactured and three strategies are mainly utilized:

- Push production
- Pull production
- Hybrid push/pull production

2.2.13.1 - Push production

Mass production is based on producing large quantities obtained by a forecasted demand regardless of the actual pace of work. This is called push production because it is not based on the actual demand but on a forecast of this one so the company are forced to push the products on the market. If the forecast is not precise or something occurs when the forecasted products are ready to enter the market the risk of unsold goods are very high.

2.2.13.2 - Pull production

Pull production is a method in which downstream activities refer their needs to upstream activities; the main target of the pull logic is to eliminate overproduction and having, theoretically, no stock in a warehouse; pull production is a major key component of a complete JIT production system. There are three types of pull production systems:

- Supermarket Pull System
- Sequential Pull System
- Mixed Supermarket and Sequential Pull System

Supermarket Pull System (Figure 11) is the most common type of pull system and is widely used; each process has a store that holds an amount of each product it produces and they are commonly called supermarket. Each process warns to replenish what has been picked from its supermarket. When material is withdrawn from the supermarket by the downstream process a Kanban card, or other type of signals, will be sent to the upstream supplying process to withdraw the product; what was withdrawn will be authorized to be replaced by the upstream process. Each process is referred to its supermarket for the replenishment so the management is simple and kaizen opportunities shows. The disadvantage of a supermarket pull system type is that a process must carry an inventory of all part numbers it produces which can be large and can become rapidly difficult to manage.

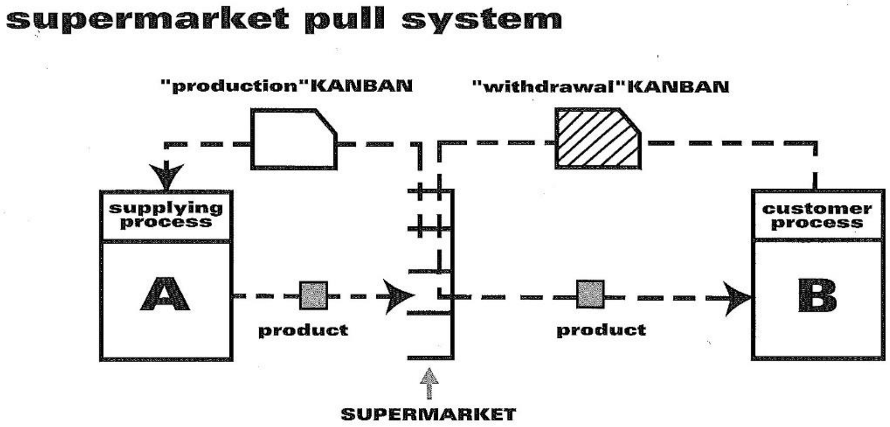


Figure 11 – Supermarket pull system (Lean Enterprise Institute, 2012a)

A sequential pull system (Figure 12) is used when there are too many parts to be hold in the inventory of each supermarket; this type of system is used when products are produced with a made-to-order system assuring overall system inventory is minimized. In a sequential system, the scheduling planners have to find the right mix for producing the right quantity of products; this can be done by using an heijunka box to place production kanban cards, normally at the beginning of each shift. These production instructions are forwarded to the process at the upstream end of the value stream; often they are given in the form of a "sequence list". Every following process produces in sequence the items delivered to it by the previous upstream process. The First-in First-out (FIFO) logic of individual products must be maintained throughout the process. A sequential system maintains short and predictable lead times creating pressure along the production chain. The customer demand must be well analyzed to be able to make this system work efficiently. When orders are difficult to predict, production lead time must be very short or an adequate store of finished goods must be held. A sequential system requires strong management skills to be maintained; kaizen may be a challenge on the shop floor.

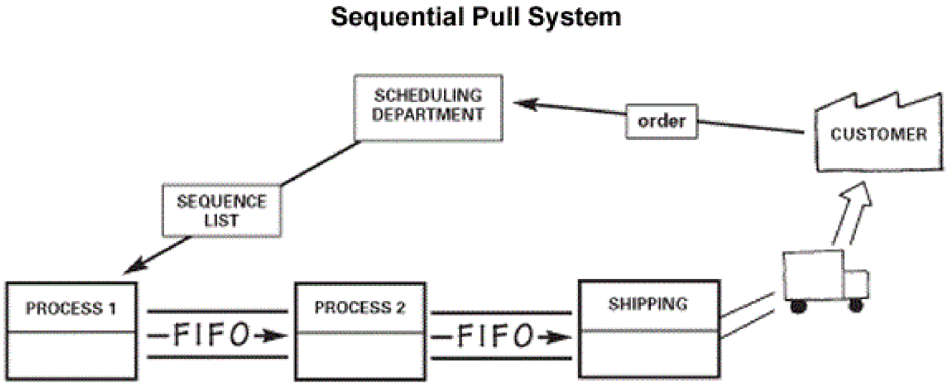


Figure 12 – Sequential pull system (Lean Enterprise Institute, 2012a)

Supermarket and sequential pull systems can be mixed together (Figure 13); this system may be appropriate when applying Pareto's rule with a small percentage of part numbers accounting for the majority of daily production volume. An analysis can be done to segment part numbers by volume into types:

- A (high)
- B (medium)
- C (low)
- D (infrequent orders)

D-type volume represents special order or service parts; handling these low-volume items requires a special D-type Kanban card representing not a specific part number but rather an amount of available capacity. D-type products' sequence of production is determined by the method that the scheduling team uses for sequential pull system part numbers. This type of mixed pull logic enables the application of both supermarket and sequential systems and the benefits of each one are obtained, even in production environments where the customer demand is complex and diversified. The two systems can work together side-by-side throughout the entire value stream or can be restricted for a specific part number at different locations along its individual value stream. On the other side, a mixed system can be more difficult for balancing work and identifying abnormal conditions that can occur; this can lead to a more stressful management of kaizen. Therefore, a continuous check of the system is required to make a mixed system work effectively.

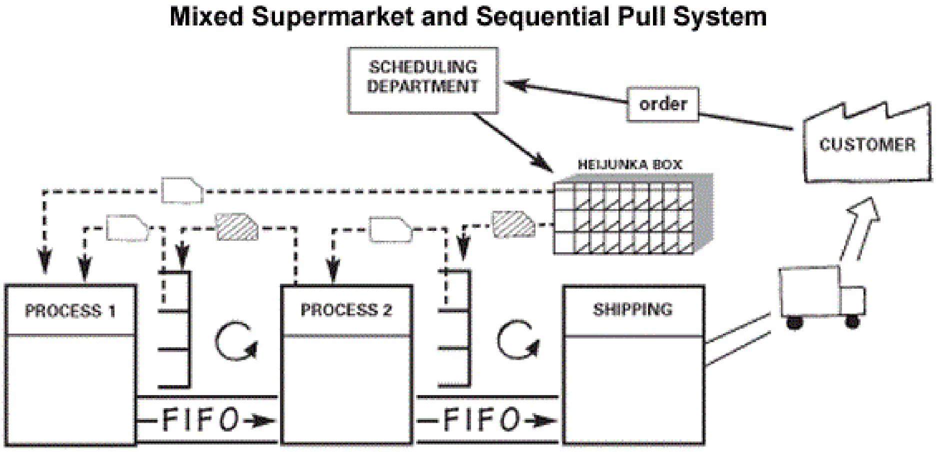


Figure 13 – Mixed Supermarket and Sequential pull system (Lean Enterprise Institute, 2012a)

When a downstream operation gives information to the upstream operation, whether within the same plant or in a separate one, a card called kanban is used to signal which part or material is needed, the quantity needed, and when and where it is needed. Nothing is produced by the upstream process until the downstream process report a need. This is the opposite of a push logic in which production is calculated on forecasts and this can lead to a general increase of costs, if forecasts are wrong, including:

- Waste of human resources

- Waste of financial resources
- Creation of stocks of raw material
- Costs related to the management of warehouses

On the contrary a pull production logic provides that the raw materials to be processed are introduced into the process line only in the moment in which the relative need occurs; the production flow through the company is pulled by demand and not pushed and some consequences are immediate:

- Reduction of overproduction's muda
- Reduction of the amount of semi-finished and finished products
- Reduction of the risk of obsolescence
- Reduction of used space in warehouse
- Reduction of WIP

To achieve all these goals, we can use some different tools to obtain multiple improvements like production levelling, setup time reduction and, generically, waste reduction. Hereafter a brief description of the most common ones:

- Kanban
- Cellular manufacturing
- Total quality management
- 5S
- Standard work
- Value stream map

2.2.13.3- Hybrid push/pull production

A hybrid push–pull strategy is usually used when uncertainty in demand is high and while economies of scale assume a crucial factor in order to reduce production and delivery costs. Normally pull-based strategy production is followed when is difficult to make production decisions based on long-term forecasts; on the other side, the logistics and distribution department prefer a push-based strategy to take advantage of economies of scale to reduce transportation cost. Hybrid push/pull production is normally used in assembly-to-order environment; raw materials can be machined at a semi-finished products level where next operations are controlled by customer' demand. Using this production layout, the upstream stations will be a push-type production while the following downstream stations are pull-type production.

2.2.14- Kanban

Kanban is a signaling system for replenishment of used materials; it's used to avoid the typical high costs of warehousing raw materials. Kanban cards are the most common example of these signals and the most used type; they are a card stock in which information such as part name, part number, external supplier or internal supplying processes and many more information are written. A bar code may be printed on the card for tracking. Kanban can have different structure like triangular shape plates or electronic signals, or many other shapes that can be useful to carry the needed information. Kanban have two functions in a production operation, aside the shape that will be used:

- Learn processes to making products
- Learn operators to moving products

The first use is called production kanban and the second one is called withdrawal kanban. Production kanban gives to an upstream process the type and quantity of products to be done by a downstream process. In the simplest form, a card corresponds to one container of parts which the upstream process will make for the supermarket in front of the next downstream process. Considering a large batch situation, a signal kanban (Figure 14) is used to start production only when a minimum quantity of containers is obtained. Signal kanban has a triangular shape and they are commonly called triangle kanban.

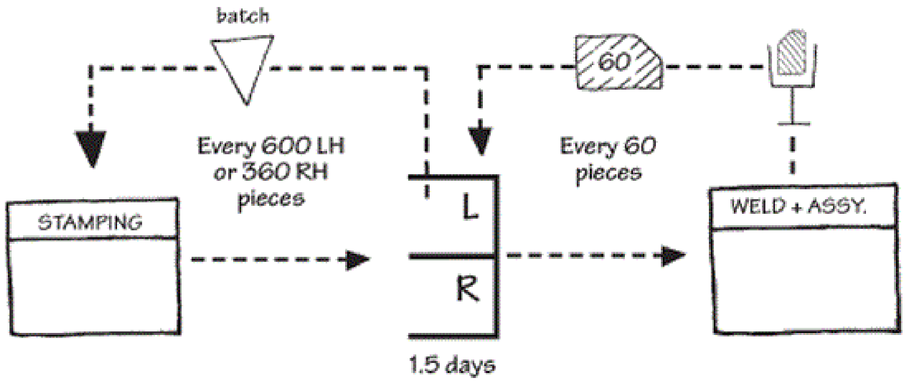


Figure 14 – Signal and withdrawal kanban (Lean Enterprise Institute, 2011b)

Triangle kanban is the standard kanban card used in LM for scheduling a batch production process but it is only one type of signal kanban; other basic ones for controlling batch operations includes:

- Pattern production
- Lot making

Pattern production delivers a pattern or a fixed sequence of production that is repeated continually although the actual amount produced each time in the process can be unfixed and diversified according to customer needs. A lot-making board

(Figure 15) means creating a physical kanban for every container of parts in the system so, when the material is taken from the market, the kanban is moved to the production process and displayed on a board highlighting all part numbers.

The returned kanban card indicates inventory that has been consumed in the market and unreturned cards represent inventory still in the market. When predefined trigger points are achieved the production operator begin to make product for replenishing the material in the market. Information come back to the production process more often thanks to the lot-making board by using smaller increments than the signal kanban; a visual representation of inventory consumption is also provided and can highlight emerging problems in the central market. On the other side using the lot-making board may require many kanban cards that has to be brought back in a reliable way to give accuracy at the batch board. Discipline is required for both schedulers and supervisors to prevent unnecessary inventory built in advance respect of when needed.

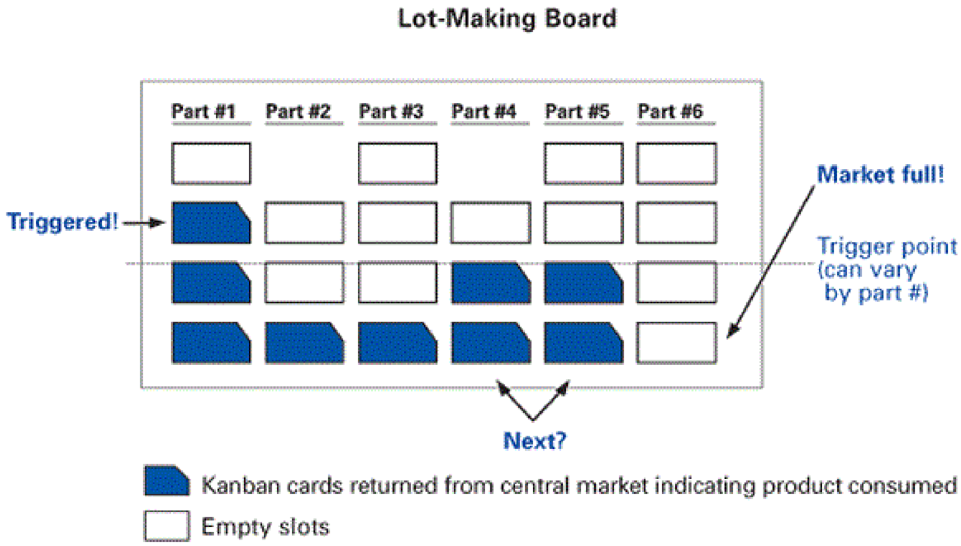


Figure 15 – Lot-making board (Lean Enterprise Institute, 2011b)

Withdrawal kanban (Figure 16) is the authorization signal for the transmission of parts to a downstream process; they normally are two types:

- Internal or inter-process kanban
- Supplier kanban (for withdrawal to an external supplier)

The first one is often used for withdrawal from an internal process or between two processes and the last one is referred to use with external supplier. Creating an effective pull system means that production and withdrawal kanban must work together; an operator removes a withdrawal kanban when using the first item in a container at a downstream process. This kanban is left in a close collection box and is subsequently picked up by a material handler; when the material handler comes back to the upstream supermarket, the withdrawal kanban is placed on a new container of parts and delivered to the downstream process. When the container is picked up from the supermarket the production kanban that is inside the container is removed and placed in another one. The material handler returns this kanban to the upstream process, where it signals the need to produce one additional container of parts. A true pull system is reached while no parts are produced or moved if no kanban card are present.

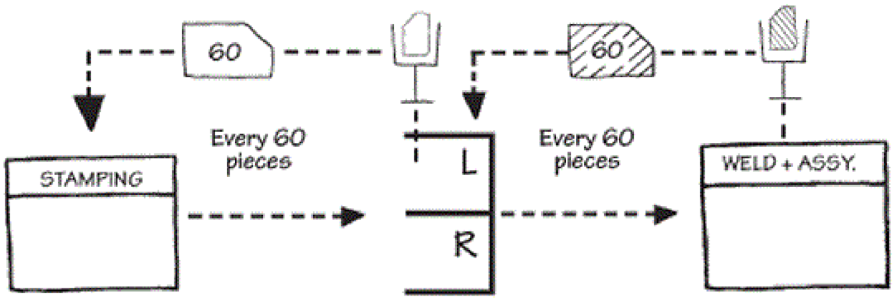


Figure 16 – Withdrawal kanban (Lean Enterprise Institute, 2011b)

There are six rules for using kanban effectively (Lean Enterprise Institute, 2008):

- Customer processes order goods in the precise amounts specified on the kanban
- Supplier processes produce goods in the precise amounts and sequence specified by the kanban
- No items are made or moved without a kanban
- All parts and materials always have a kanban attached
- Defective parts and incorrect amounts are never sent to the next process
- The number of kanban is reduced carefully to lower inventories and reveal problems

Kanban can be even implemented between the last production process and the process of delivery to the final customer; at the moment in which the customer uses the product the kanban card attached to the package and the empty container returns to its supplier; when the supplier receives the returning kanban card the chain of production processes can be activated to fulfill the customer request. Once the finished products are produced they are stocked in the finished products warehouse, which is used as a buffer by the customer. Process continuity is insured along the entire value chain with a mechanism that allows the realization of a mix-levelled production because the product follow the kanban sequence; this is contributing to the achievement of greater integration and an increasing competitiveness of the whole SC. The advantages given by the adoption of kanban are:

- WIP reduction
- Reduction in the amount of finished products stocked in warehouses
- Greater production flexibility

- Lead time reduction
- Costs reduction
- Delivery time improvement

Modified type of kanban system also exist; an extensive literature review about this topic has been carried out by (Junior and Filho, 2010).

2.2.15 - Cellular manufacturing

Cellular manufacturing is a method for organizing the process of a specific, or similar, product into a group to facilitate the operations done by the operator; it is an approach in which equipment and workstations has a layout studied to facilitate the production of small lots in a continuous flow of processes. The key fact about manufacturing cell is related to the fact that all the mandatory operations to produce, or assembly, a component are performed in close proximity allowing for quick response between operations when problems, or other issues, arise. Normally cellular manufacturing has a working space with a U-shape layout (Figure 17).

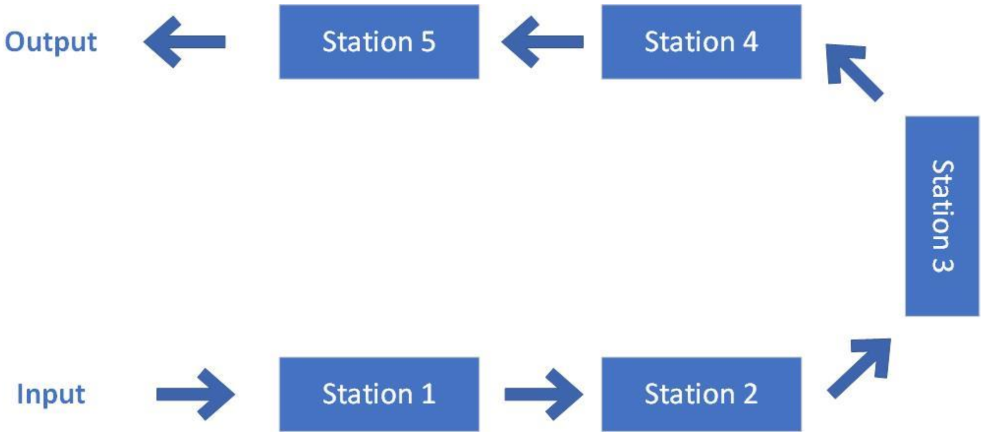


Figure 17 – U shape cell layout

Workers emplyed in manufacturing cells are normally cross-trained and able to perform multiple tasks on different machine as needed. In traditional manufacturing environments machines performing similar task are placed close together because this layout is more robust regarding machine breakdowns; besides they have common jigs and fixtures in the same area with high levels of demarcation. On the other side, cellular manufacturing group together all the machines according to the families of parts produced that lead to an advantage because the material's flow is significantly improved and reduce the distance covered by materials, inventory and people resulting in increased lead time.

2.2.16 - Total quality management

Total quality management (TQM) is a philosophy of continuous improvements based on the customer needs. This method embraces the whole factory at every level without distinctions; continuous trainings for managers and employees as well as problem-solving mindset are just some of the key point of LT. This approach has to be extended to all departments, employees, and managers that are responsible for kaizen so that products and services meet, or exceed, customer expectations. The Total Quality Control (TQC) methodology manage processes using the plan-do-check-act (PDCA) cycle and when a problem arises statistical tools can help to solve them. TQM key concept is about the idea that quality is the responsibility of all employees, managers, and senior managers and is a pillar of lean transformation inside a company; LT is widely used at a production level while TQM is commonly used at a management level.

2.2.17 - 5S

5S is a method focused on the work place's best organization and the best procedure for doing a task. The 5S method allows you to standardize the management of workplace and accurately define the rules to respect the defined standards. This tool is particularly useful to trigger the continuous improvement process, using current standards as a starting point to achieve improved new standards. Method application starts with choosing a pilot area in one or more departments and focus the attentions on the obtained results highlighted in a short period of time. For the company is of fundamental importance to have success on the pilot area to be able to extend the activities to the entire company creating a virtuous cycle. For the implementation of the 5S system reference workers are formed; they will explain to their colleagues the concepts of the process to avoid misunderstanding. These processes are milestone for the implementation of a lean approach. 5S is an acronym of five Japanese words:

- Seiri
- Seiton
- Seiso
- Seiketsu
- Shitsuke

2.2.17.1- Seiri

Seiri stand for choose and separate; from all the item used choose the needed ones from the unneeded ones and separate it; then discard the unneeded. So seiri is related to the removal from workstations of everything that is not used in the production process. The correct application of this point allows to make optimum use of the available space, reduces the loss of time for the research of materials, equipment and documents. Moreover, seiri ensures respect for the principles of

JIT by having the right material at the right time in the right amount. Reduction of problems and interference in the workflow are obtained with a higher quality of the products and an increase in productivity. During the phase of separation between useful and not-useful material a consideration on how frequently they are used must be done. Without Seiri this problem arises:

- Departments and workstations become increasingly full
- Equipment and tools in good, bad or mixed conditions
- Equipment amount not adequate
- Difficulty to check the presence of necessary tools.

2.2.17.2- Seiton

Seiton stand for arrange and organize. Neatly arrange the used items in an efficient way. The second step of the 5S is order: objects and tools must be arranged in such a way that they are easy to identify, use and store. This is very important since it allows to eliminate many wastes of time in productive activities and guarantees, as the previous phase, the observance of the principles of JIT. The arrangement and the organization allow to obtain a greater fluidity and linearity in productive activities; this concept is the key point of standardization; a system that allows you to complete the procedures and operations in the most efficient way. The workstation must be in order because this is the only way possible to carry out the standardization in an effective manner; considering both where, and how, the materials are placed is fundamental. Minimize waste and having the possibility to analyze the causes of them is the application target of seiton. Without seiton this problem arises:

- Loss of materials and equipment

- Time waste
- Workspaces not functional
- Frequent use of tools that are not easily accessible

2.2.17.3- Seiso

Seiso is referred to the cleaning and washing workplaces, equipment and tools operations. The third one is easier to explain and perform: general cleaning of the production line and of the work environment in which it is placed. Dirt is everything and interferes, blocks, attacks or damages the work environment and people. After a first general cleaning the areas of intervention must be located and delimited. In fact, there is a close relationship between the cleanliness of the workspace, the wear of the machines and quality defects; the workspace cleaning must become a habit. A good and continuous cleaning in fact ensures a healthy environment, a better safety and a better quality of the products and equipment.

2.2.17.4- Seiketsu

Seiketsu stands for standardize and is the result of a correct application of the first three phases, with the aim of making them a daily habit and ensure that they are maintained and improved in time; it is only by following this philosophy you can have a real and effective implementation of the fourth step. There are three main steps for standardization:

- Define the processes managers
- Integrate processes in normal work activities
- Control and maintenance of the processes

The typical instrument for the control of seiketsu is the visual management; it allows anyone to verify at any time the status of the production system, locate any faults and understand the causes. The main characteristic of this tool is its transparency and easiness in communication and information management, obtained mainly through visual signals, to make the information usable by anyone. Standardize means to behave and act having as a point of reference a common model easily understandable by everybody and every action must lead to a continuous improvement.

2.2.17.5- Shitsuke

Shitsuke can be translated in discipline that is a recurring concept in Japanese culture and in lean philosophy; it is the mindset needed to perform the first four S as well as sustaining more other typical lean practices. The fifth step consists in making sure that the procedures put in place with the first four Ss are maintained. No matter how well they have been applied for the first four steps but the system may not operate for long time if maintenance phase is skipped. The final objective will be to support the maintenance phase necessary to obtain the benefits required by the company. The first part of the maintenance is based on the fulfillment of optimal conditions for applying the 5S system; the second part request a demonstration of employees' commitment to apply the 5S. Guaranteeing and supporting the standard achieved with the first three steps is possible through:

- Continuous monitoring of the standards
- Effective communication
- Employees responsibility
- Employees motivation
- Continuous training program

Verification tools must be defined, for example to check list needed to evaluate periodically the adoption of the standard. Audits can also be created, as in Figure 18, which will be done periodically to keep track of progress in the applications of the 5S method in time.

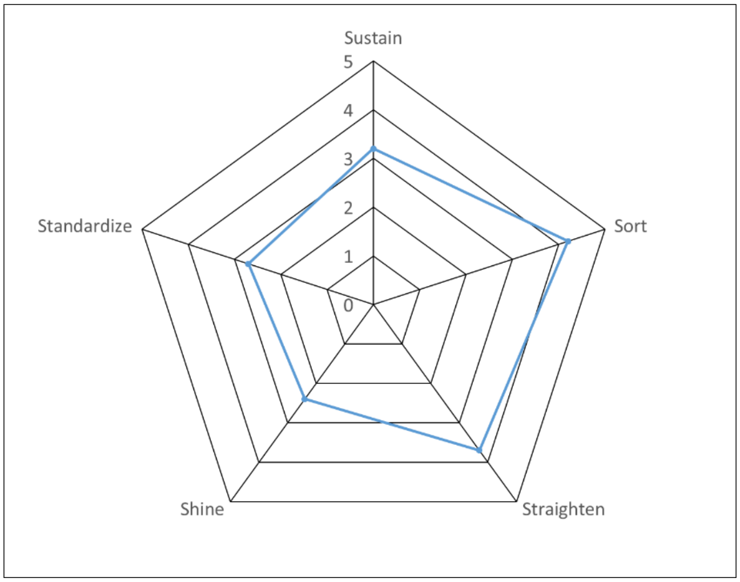


Figure 18 - 5S radar chart

5S are translated in English as:

- Sort
- Straighten
- Shine
- Standardize
- Sustain

A sixth S has unofficially been added and stand for safety that is a key factor in enterprises.

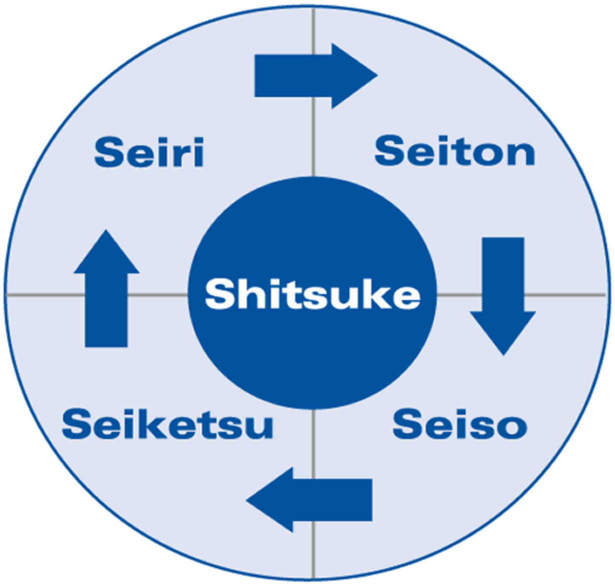


Figure 19 – 5S cycle (Lean Enterprise Institute, 2011a)

5S' key point is related to the comprehension that the effort to apply these rules has to be continuous, systematic and organic (Figure 19); it must not be considered as an unfixed stand-alone program.

2.2.18 - Value stream map

Value stream map (VSM) is a representation step by step of materials and information flows involved in a production process that bring a product from order to delivery. VSM is useful to visualize the flow of the materials starting from the raw ones to finished products and considers the whole flow of both information and materials through the SC; it shows even the value-added processes and non-value-added processes. Value-stream mapping represents different points in time with the purpose of finding opportunities for improvement. The main goal of VSM is to identify all the types of muda and try to eliminate them (Rother and

Shook, 2009). VSM is used referred to two states for a better understanding of the progress of the lean transformation:

- The current state
- The future state

2.2.18.1- Current state map

A current-state map (Figure 20) follows a product's path from order to delivery to determine the current production conditions; a second goal is to obtain significant differences between real processes and the documented processes and procedures. The main targets of VSM are:

- Focus on the flow instead of processes
- Find the reason of waste in the flow
- Train operators to understand the whole flow
- Highlights aspects of flow improvement

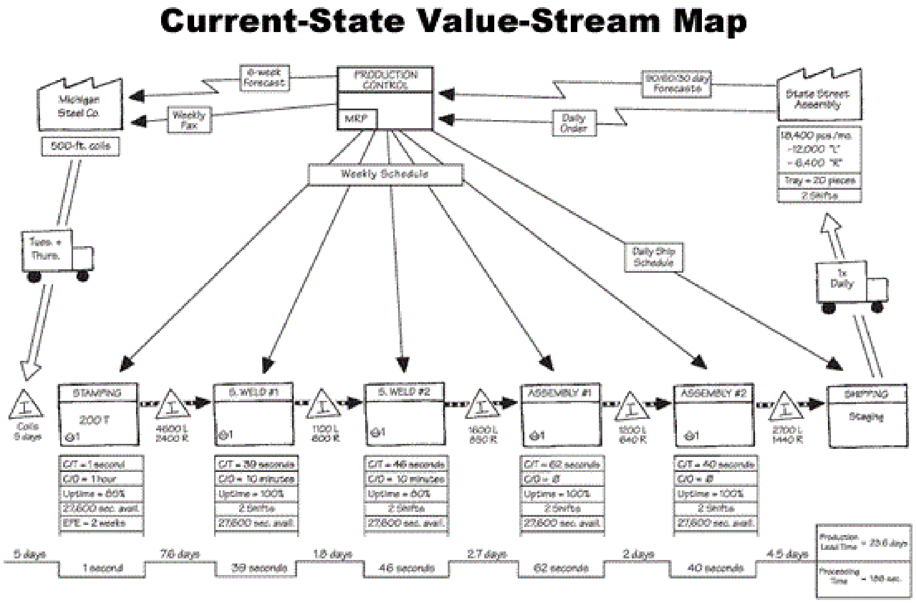


Figure 20 – Current state map (Lean Enterprise Institute, 2010)

Often this map is mandatory to build an ideal state map that is the current state map considering the removal of the wasteful practices identified. Ideal state map has to be challenging in order to satisfy the kaizen philosophy and represent the absolute ideal of your process with no waste.

2.2.18.2- Future state map

A future state map (Figure 21) shows the higher level of performance that can be reached if the opportunities for improvement identified in the current-state map are fulfilled.

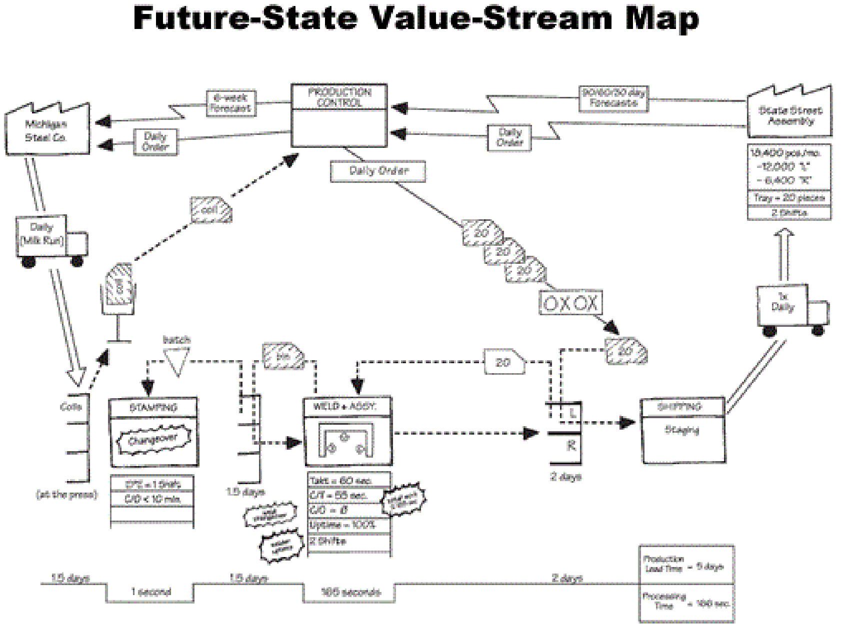


Figure 21 – Future state map (Lean Enterprise Institute, 2010)

The future state value stream map is the first step between your current state map and the ideal state that represent the enterprise target. The areas to be improved highlighted from the current state map typically are;

- Cycle time reduction
- Setup time reduction
- Batches amount reduction
- Improve overall quality performance
- Implement kanban

As the ideal state map represent the waste-free production process, it can be a challenging task but even not reachable. It is important to understand that changes must be done slowly for preventing problems in the production process; future state map represent one step to the ideal state map and when this step has been completed the future state map become the actual state and a second step can be achieved.

2.2.19 - Single minute exchange die

Single minute exchange die (SMED) refers to a technique needed to perform operations under ten minutes, meaning the number of minutes expressed from a single digit. The SMED system is the most effective way to reach JIT. The main goal is to check the sources of variation and eliminate the need for adjustments on equipment, machines and plants; a diversified production with small batches can not be obtained without the SMED. The SMED is therefore essential to the stability of the process and it is the most effective way to obtain quality product even with complex costumer demand. Giving a straight control of the setup operations can drastically reduce production times leading to the possibility of producing small batches (McIntosh *et al.*, 2000). The SMED focuses on the set-up that is any activity that takes place between the completion of the production of the last article of one type and the completion of the first product of the next type. The SMED project starts initially with the operators training that is carried out involving the main actors of the productive sector in which it is desired to bring the improvement. The second part is about creating a working team and identify team leaders. Choosing a machine that has average setup-times compared the other machines of the company is the third step; this machine will gather the necessary data to study the operation and the setup-times. Recording the workstation during the complete process will show all the relevant wastes and inefficiencies. At this point the whole team will analyze the recording and thus identify 4 key parameters:

- Necessary, or creating-value, work
- Unnecessary work

- Internal setup
- External setup

The creating-value work can be standardized in order to be improved with kaizen; the unnecessary activities has to be removed. Internal setup refers to a non-working machine state: they are operations like installation and removal of tools and equipment; external setup is referred to the working machine time; they can be, for example, transportation of tools from and to the warehouse. Internal activities are the primary ones to be optimized by simplifying the workstation space with the 5S tool. Subsequently external operations will also be improved. Standardizing the processes adopting a procedure is the last step that will have to be improved with kaizen; the tools needed in the workstation should also be placed in a standard point. The SMED will lead to:

- Quality improvement
- Warehouses reduction
- Flexibility
- Lead time reduction
- Safety improvement

2.2.20- One-piece flow

One-piece flow represent the progress of the material from a production process to the next one a piece at a time following a continuous flow; the material passes through the departments in a fast lane and there is a sensible reduction of intermediate stocking. One-piece flow method is incompatible with process-layout's companies where the production operations are performed in departments characterized by similar processing. The types of layouts are:

- Layout for job
- Layout for product
- Fixed-position layout
- Hybrid Layout

Layout for job, best known as job-shop, is where the machines are grouped by the nature of skills and technological processes involved. Layout for product is a linear organization of workstations to produce a specific product type. In the fixed-position layout product can not be moved due to large size dimension, bulky dimension or fragile; normally the materials converge on the place to avoid transportation. Hybrid layout can be of two types:

- Cellular manufacturing
- Mixed-model assembly lines

Cellular manufacturing is a layout where machines are grouped according to the operations needed for similar items that require similar processing and cells are named these groups; a cellular layout is an equipment-driven layout configured to support cellular manufacturing. Group technology (GT) is the name of the technique that group production processes into cells; it is necessary to identify parts with similar design characteristics and similar process attributes. Cross-trained workers are essential in cellular layouts so that they can operate all the equipment within the cell and be responsible for its output. Some of the advantages of cellular manufacturing include:

- Cost
- Flexibility

- Operator’s motivation

Using a cellular manufacturing layout lead to faster processing time, less material handling, less WIP inventory and reduced setup time all of which contributes to cost reduction: cellular manufacturing works with the production of small batches which increased the flexibility of overall production chain. Operator’s motivation is increased due to the cross-training needed to run every machine in the cell and the responsibility for their cells' output; more autonomy and job ownership are given to operators. Mixed-model assembly lines use a JIT logic to produce a variety of codes on the same line; it is the practice of assembling several distinct models of a product on the same assembly line without changeovers and then sequencing those models in a way that levels the demand for upstream components. The target is to smooth the demand on work-centers, manufacturing cells or suppliers in the upstream process to reduce inventory and changeovers and continuously improving operation through kanban. One-piece flow is a challenging target not always reachable but it represents the fifth principle of LT, perfection, which must be the goal we tend to. Sometimes a problem can occur when two, or more machines, share a resource; in this case the upstream machine can not serve both value-streams and therefore there is a need to stock resources to keep them simultaneously operating; for this reason, in the lean approach, is preferred to adopt small-sized machines to keep the flows separated and working without WIP. In order to fully achieve the goals of LM it is convenient to arrange the machinery within a U-shaped cell where, at input, are located the incoming raw materials and, in the output, outgoing products. Inside a cell the machines are arranged in line and there is no inter-operational buffer because the flow is continuous, levelled and synchronized so that every piece flows with continuity from one machine to the next one; each cell is dedicated to the production of a few product types; the guiding principle is the grouping of products in families that have similar characteristics and technology. The fundamental steps of the design of a cell are:

- Flow mapping
- Part Routing Matrix
- Cell Highlighting
- Process engineering
- Layout study
- Heijunka

Flow mapping, also known as spaghetti chart, starts with plotting of the whole flow acting inside the plant; the meaning is to physically follow the product throughout the whole production process. The products references are chosen comparing volumes, sales revenue or important characteristics of the production processes. All the product movements between work-centers, assembly or control stations, intermediate waiting buffer and warehouses are reported on the layout, creating a spaghetti chart. Wastes and inefficiencies are highlighted due to the continuous movements, returning-flows and crossed-flows. This is reported in the part routing matrix; a matrix where on one axe are indicated the products, semi-finished products or raw materials and the other axe have steps, operations or machines; after inserting all the data the matrix is diagonalized to group the codes that have similar product cycle by changing the order of the row and column of the first-step matrix. The expected result is the identification of the families of products that are technologically similar and their grouping by flow analogy in production cells. The advantages that can be obtained are relative to:

- Efficiency using the company space
- Better knowledge of the overall operation of the process

- Better communication between working teams
- Reduction of the operators' movement
- Workspace optimization
- Better production flexibility
- Efficient materials handling

The cells must contain all the equipment, tools and resources needed to produce; workstations must be made with ergonomic criteria so that the movements are short, coordinated and simple. The most important advantage of this type of layout is the flexibility to the increase or decrease in workers' number in case of production variations. Variations in demand can be satisfied by increasing or decreasing the number of workers in U-shaped cell. A well-designed layout can not guarantee the achievement of flexibility by itself. The focus goes on cross-trained operators; the training of the individual takes place through a system called job rotation according to which each operator is formed to carry out each job request by the departments he works in. After a certain period of time the operator gain experience in multiple task becoming a cross-trained operator.

2.3- HVLV

There are 3 fundamental questions arising from the concept of HVLV manufacturing:

- Establishing a formal definition of HVLV environment
- Which are the companies' business sectors based on this environment
- Applicability of the LM in this environment

Before establishing a definition of HVLV can be useful to understand which are the production environments majorly recurring in research. Based on (Wikner and Rudberg, 2005; Gosling *et al.*, 2007; Staudacher and Tantardini, 2012) the definition of HVLV production environments is related to SC structures and the customer order decoupling point (CODP). Generally, there are 6 types of SC:

- Engineer to order (ETO)
- Buy to order (BTO)
- Make to order (MTO)
- Assembly to order (ATO)
- Make to stock (MTS)
- Ship to stock (STS)

ETO SC is a demand-driven manufacturing process in which the component is designed, engineered, and built to specifications only after the order has been received; an extensive literature review have been carried out by (Gosling and Naim, 2009). BTO SC is a demand-driven production approach where a product is scheduled and built in response to a confirmed order received for it from a final customer. MTO SC is a manufacturing process in which manufacturing starts only after a customer's order is received. ATO SC requires that the basic parts for the product are already manufactured but not yet assembled; once an order is received the parts are assembled quickly and sent to the customer. MTS SC products are manufactured based on demand forecasts. In STS SC products are manufactured and shipped directly into the manufacturing stock without the traditional goods inwards inspection that can be eliminated or at least significantly reduced. Figure 22 describe the different type of SCs focusing on the level of standardization and customization and the line that runs through the different structures shows the point at which the customer order enters the supply chain. (Wikner and Rudberg, 2005; Gosling *et al.*, 2007).

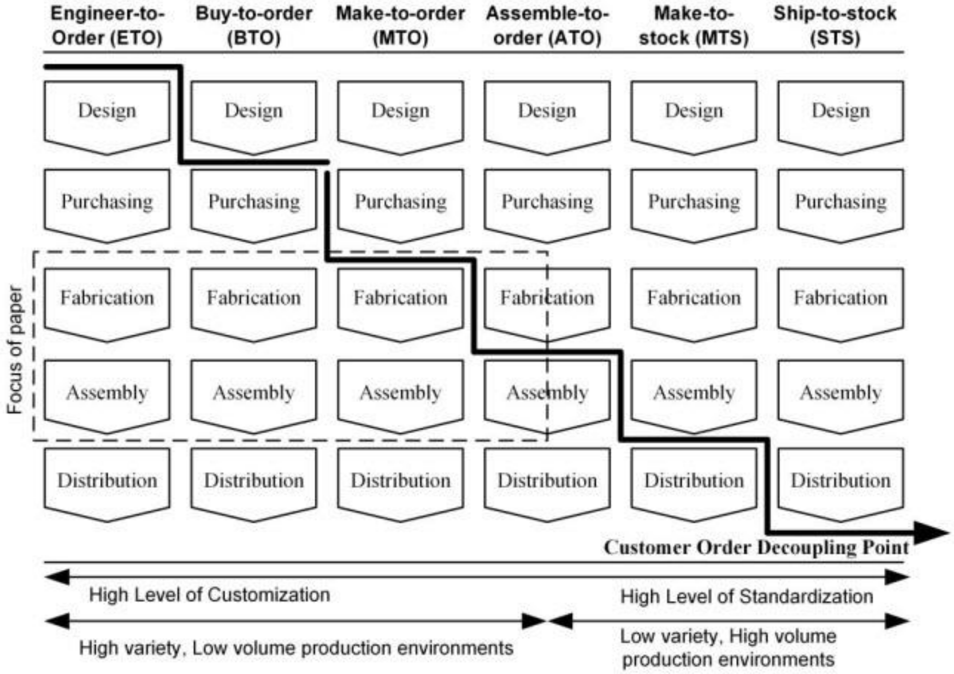


Figure 22 - The six different SC structures (Gosling *et al.*, 2007)

As reported in the literature, "HVLV production environments include all of the following SC structures: ETO, BTO, MTO and partly ATO. The other three structures, ATO (partly), MTS and STS describe LVHV production environments.

In addition to the SC structure definitions in relationship to the COPD, other aspects of the HVLV production definition are related to the lot size such as unique production or small batch production. The designations ETO, BTO, MTO and unique production indicate mostly an OKP production" (Buetfering *et al.*, 2016). Considering the aspects of types of SC and CODP a definition of HVLV production environments could be: "HVLV production environments includes the OKP as well the small batch production environments" (Buetfering *et al.*, 2016). HVLV manufacturers can exhibit both ETO and MTO characteristics depending on the degree of product customization that the company is able to reach. If the required products need an in-depth engineering analysis the company will more likely be ETO; instead, if the products require less customization capability the company will probably be MTO. HVLV companies can also selling their resources acting as manufacturing service providers (Katic and Agarwal, 2018). To complete an overview of the HVLV production environments some companies' type that could represent the business sectors, without pretending to be exhaustive, are reported:

- High Fashion industry
- Leather industry
- Jewellery industry
- Watchmaker industry
- Yachting industry
- Luxury cars industry
- Aerospace industry
- Defence industry
- Biomedical industry
- Heavy equipment industry
- Earth-moving equipment industry

Even if, at a first glance and based on the products they made and sells, the sectors seem to be very far away from each other, it's possible see a general context underlying the different types of industry (Jina, Bhattacharya and Walton, 1997). For example, the first six companies can be grouped in the luxury field; producing a yacht is more complex than producing a luxury ring but this companies shares the same OKP-to-small-batches type of order and product complexity. As reported by (White and Prybutok, 2001) another possible definition of HVLV could be "non-repetitive companies" where all the production stages operate on a non-repetitive base (Staudacher and Tantardini, 2012). SMEs competing in a HVLV environment have to be both flexible and highly efficient in order to reach the organisational ambidexterity (Katic and Agarwal, 2018). HVLV companies provides tailored manufacturing services to be able to customize the product as much as the customer demand (Amaro, Graça; Hendry, Linda; Kingsman, 1999; Adrodegari *et al.*, 2015) but achieving a profitable business can be challenging (Land and Gaalman, 2009). The existing literature is focused on the improvement of operational efficiency like production planning and control (PPC) (Hendry, Huang and Stevenson, 2013; Adrodegari *et al.*, 2015; Cransberg *et al.*, 2016) and the adoption of mass-customisation principles (Thomassen and Alfnes, 2017). Improvement of operations' efficiency practises increase profitability (Bezerra and da Silva, 2015) and competitive advantage (Amaro, Graça; Hendry, Linda; Kingsman, 1999) In conclusion, a formal definition of HVLV environment has been set and some HVLV companies' business sectors has been identified; the next paragraph will investigate the possibility of using LM in HVLV context.

2.4- LM and HVLV

In the previous chapter a LR of the main concept, LM and HVLV, utilized as foundation of this work has been introduced; LM has been proven one of the best way to increase operational performances and HVLV production system represent a challenging environment for SMEs (Slomp, Bokhorst and Germs, 2009). The next step to deepen the knowledge about LM and HVLV topic has been searching the related literature. As introduced in Table 3, there is more terms used when defining an HVLV environments; for this reason, all the possible variations have been included in the string for the search engines and follows:

- ("high-variety" OR "high-variance" OR "high-mix") AND "low-volume"

LM and LP are considered equivalent but both has been considered in order to achieve a better result as:

- ("lean manufacturing" OR "lean production")

The complete search string is:

- ("high-variety" OR "high-variance" OR "high-mix") AND "low-volume" AND ("lean manufacturing" OR "lean production")

The search engine research's results are:

Search engine	Number of papers

Scopus	33
Science Direct	78

The list of papers, excluding books, on the LM and HVLV topic are 67 and reported in Table 6.

#	Authors	Title of Research
1	Abele, E., Chryssolouris, G., Sihn, W., Metternich, J., ElMaraghy, H., Seliger, G., Sivard, G., ElMaraghy, W., Hummel, V., Tisch, M. and Seifermann, S.	Learning factories for future oriented research and education in manufacturing
2	Aitken, J., Childerhouse, P. and Towill, D.	The impact of product life cycle on supply chain strategy
3	Alford, D., Sackett, P. and Nelder, G.	Mass customisation — an automotive perspective
4	Barenji, A.V., Barenji, R.V. and Hashemipour, M.	Flexible testing platform for employment of RFID-enabled multi-agent system on flexible assembly line
5	Bjerklie, S.	Airline industry: Up, up and away: Highly specialized sector offers many opportunities for metal finishers, but requires strict adherence to end-user and regulatory requirements
6	Bohnen, F., Maschek, T. and Deuse, J.	Leveling of low volume and high mix production based on a Group Technology approach
7	Bohnen, F., Buhl, M. and Deuse, J.	Systematic procedure for leveling of low volume and high mix production
8	Brown, S. and Fai, F.	Strategic resonance between technological and organisational capabilities in the innovation process within firms
9	Brown, A., Amundson, J. and Badurdeen, F.	Sustainable value stream mapping (Sus-VSM) in different manufacturing system configurations: application case studies
10	Cevikcan, E. and Durmusoglu, M.B.	An integrated job release and scheduling approach on parallel machines: An application in electric wire-harness industry

11	Cheikhrouhou, N., Hachen, C. and Glardon, R.	A Markovian model for the hybrid manufacturing planning and control method 'Double Speed Single Production Line'
12	Coelho, S.M., Pinto, C.F., Calado, R.D. and Silva, M.B.	Process Improvement in a Cancer Outpatient Chemotherapy Unit using Lean Healthcare
13	Conner, G.	Don't let wasteful tasks slow you down: Lean manufacturing eliminates meaningless activities from the shop floor while boosting productivity and efficiency
14	Conner, G.	Common sense approaches to eliminating manufacturing waste: Lessons from the shipping industry can help job shop owners "scrape" the excess from their operations
15	Corbett, L. and Campbell-Hunt, C.	Grappling with a gusher! Manufacturing's response to business success in small and medium enterprises
16	Cortes, H., Daaboul, J., Duigou, J.L. and Eynard, B.	Strategic Lean Management: Integration of operational Performance Indicators for strategic Lean management
17	da Silveira, G.J.	Effects of simplicity and discipline on operational flexibility: An empirical reexamination of the rigid flexibility model
18	Davidson, D. and MacKay, K.	Meeting the lean deburring challenge
19	Dekkers, R.	Group technology: Amalgamation with design of organisational structures
20	Deuse, J., Konrad, B. and Bohnen, F.	Renaissance of Group Technology: Reducing Variability to Match Lean Production Prerequisites
21	Dombrowski, U. and Malorny, C.	Methodological approach for a process-orientated Lean Service implementation
22	Doolen, T.L. and Hacker, M.E.	A review of lean assessment in organizations: An exploratory study of lean practices by electronics manufacturers
23	Dora, M. and Gellynck, X.	House of lean for food processing SMEs

24	ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M. and Bernard, A.	Product variety management
25	Feng, Y., Li, G. and Sethi, S.P.	A three-layer chromosome genetic algorithm for multi-cell scheduling with flexible routes and machine sharing
26	Fleck, J.	Learning by trying: the implementation of configurational technology
27	Filho, M.G., Marchesini, A.G., Riezebos, J., Vandaele, N. and Ganga, G.M.D.	The application of Quick Response Manufacturing practices in Brazil, Europe, and the USA: An exploratory study
28	Gunasekaran, A. and Ngai, E.	Build-to-order supply chain management: a literature review and framework for development
29	Gunasekaran, A. and Ngai, E.W.	The future of operations management: An outlook and analysis
30	Hon, K.	Performance and Evaluation of Manufacturing Systems
31	Huang, Y.-Y. and Li, S.-J.	How to achieve leagility: A case study of a personal computer original equipment manufacturer in Taiwan
32	Jia, F., Lamming, R., Sartor, M., Orzes, G. and Nassimbeni, G.	International purchasing offices in China: A dynamic evolution model
33	Korytkowski, P., Wisniewski, T. and Rymaszewski, S.	Multivariate simulation analysis of production leveling (heijunka) - a case study
34	Krishnaiyer, K. and Chen, F.F.	Web-based Visual Decision Support System (WVDSS) for letter shop
35	Kumar, M. and Rodrigues, V.S.	Synergetic effect of lean and green on innovation: A resource-based perspective
36	Matt, D.T., Dallasega, P. and Rauch, E.	Synchronization of the Manufacturing Process and On-site Installation in ETO Companies
37	McKay, K.N. and Buzacott, J.A.	The application of computerized production control systems in job shop environments

38	Metternich, J., Bechtloff, S. and Seifermann, S.	Efficiency and Economic Evaluation of Cellular Manufacturing to Enable Lean Machining
39	Muda, S. and Hendry, L.	Developing a new world class model for small and medium sized make-to-order companies
40	Nagalingam, S.V. and Lin, G.C.	CIM—still the solution for manufacturing industry
41	Pearce, A., Pons, D. and Neitzert, T.	Implementing lean—Outcomes from SME case studies
42	Powell, D., Alfnes, E., Strandhagen, J.O. and Dreyer, H.	The concurrent application of lean production and ERP: Towards an ERP-based lean implementation process
43	Powell, D., Strandhagen, J.O., Tommelein, I., Ballard, G. and Rossi, M.	A New Set of Principles for Pursuing the Lean Ideal in Engineer-to-order Manufacturers
44	Purvis, L., Gosling, J. and Naim, M.M.	The development of a lean, agile and leagile supply network taxonomy based on differing types of flexibility
45	Rewers, P., Hamrol, A., Żywicki, K., Bożek, M. and Kulus, W.	Production Leveling as an Effective Method for Production Flow Control – Experience of Polish Enterprises
46	do Rosário Cabrita, M., Duarte, S., Carvalho, H. and Cruz-Machado, V.	Integration of Lean, Agile, Resilient and Green Paradigms in a Business Model Perspective: Theoretical Foundations
47	Salvador, F., Forza, C. and Rungtusanatham, M.	Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions
48	Schaede, C., Seifermann, S. and Metternich, J.	Automated generation of CNC programs for manufacturing of individualized products
49	Schonberger, R.J. and Brown, K.A.	Missing link in competitive manufacturing research and practice: Customer-responsive concurrent production
50	Schonberger, R.J.	Reconstituting lean in healthcare: From waste elimination toward 'queue-less' patient-focused care
51	Shum, K.L. and Watanabe, C.	Towards a local learning (innovation) model of solar photovoltaic deployment

52	Sousa, R.	Linking quality management to manufacturing strategy: an empirical investigation of customer focus practices
53	Sousa, R. and Voss, C.A.	Contingency research in operations management practices
54	Stratton, R. and Warburton, R.	The strategic integration of agile and lean supply
55	Sundar, R., Balaji, A. and Kumar, R.S.	A Review on Lean Manufacturing Implementation Techniques
56	Sutari, O.	Process Improvement Using Lean Principles on the Manufacturing of Wind Turbine Components – a Case Study
57	Synnes, E.L. and Welo, T.	Design for Automated Assembly of Large and Complex Products: Experiences from a Marine Company Operating in Norway
58	Uusitalo, P. and Lidelöw, H.	The Struggle of Multiple Supply Chain Structures: Theoretical Overview
59	Vallhagen, J., Almgren, T. and Thörnblad, K.	Advanced use of Data as an Enabler for Adaptive Production Control using Mathematical Optimization – An Application of Industry 4.0 Principles
60	van der Vaart, T. and van Donk, D.P.	Buyer focus: Evaluation of a new concept for supply chain integration
61	van Hoek, R.	The rediscovery of postponement a literature review and directions for research
62	Villa, A. and Taurino, T.	From JIT to Seru, for a Production as Lean as Possible
63	Ward, P.T., Bickford, D.J. and Leong, G.	Configurations of manufacturing strategy, business strategy, environment and structure
64	Wiendahl, H.-P., ElMaraghy, H., Nyhuis, P., Zäh, M., Wiendahl, H.-H., Duffie, N. and Brieke, M.	Changeable Manufacturing - Classification, Design and Operation
65	Chang, Y.Y.-C. and Jones, P.	Flight Catering: An Investigation of the Adoption of Mass Customisation

66	Yin, Y., Stecke, K.E., Swink, M. and Kaku, I.	Lessons from seru production on manufacturing competitively in a high cost environment
67	Zhao, S., Grossmann, I.E. and Tang, L.	Integrated scheduling of rolling sector in steel production with consideration of energy consumption under time-of-use electricity prices

Table 6 – LM and HVLV papers list

The results obtained in Table 6 emphasize the fact that LM for HVLV environment is a field that are less explored compared to LVHV one. However, the argument shows interest due to two main reasons; HVLV companies are mainly SMEs and, normally, SMEs are the most common companies in a national productive system; the second reason is that the outlook on the future productive system is about mass customization that leads to a probable recent future in which companies will choose to be HVLV to react faster on the market.

2.5– From kanban to CONWIP

The analysis of the current literature discussed in the previous chapters point out on the possibility of using LM tools and methods in HVLV environments; levelling production, a pull system and a production progress' tool control are the most important task to achieve in order to obtain a successful LM implementation (Womack and Jones, 1996). Pull systems are a special type of material control system that aim to control the throughput times of orders by limiting the workload on the shop floor (Hopp and Spearman, 2004) and the throughput time performance in MTO environments depends on its capability to create a balanced distribution of the workload among the workstations on the shop floor. The easier way to limit the workload on the shop floor is by controlling the number of orders or limiting the workload based on the processing time of orders; unit-based pull systems are the one that control the number of orders while load-based pull systems limit the workload based on the work content of orders. (Germs and Riezebos, 2010). Unit-based pull systems that are applicable in an MTO environment are scarce (Germs and Riezebos, 2010) and the ones that seem suitable for MTO companies, that include CONWIP according to (Stevenson, Hendry and Kingsman, 2005), receives only limited attention in performance comparisons. CONWIP (Spearman, Woodruff and Hopp, 1990) stands for CONstant Work In Process and an updated systematic review has been done by (Jaegler *et al.*, 2017). CONWIP can be implemented in both LVHV and HVLV environment and, for this reason, it can be considered as a generalization of kanban even though application in pure job shop could not lead to better results (Stevenson, Hendry and Kingsman, 2005). The usage of CONWIP is simple and assumes that the articles produced are moved into standard containers; part numbers are assigned to the cards at the beginning of the production line and the numbers are matched with the cards by referencing a backlog list. Under no circumstances are workers allowed to force the start of work without a card present, even if the first process centre in the production lines is idle. The production line have a FIFO queue discipline common to all the work centres while the only exception is for rework that has the highest priority (Spearman, Woodruff and Hopp, 1990). When the container exits the production line the card came back at the beginning of the line so new work can be release as represented in Figure 23:

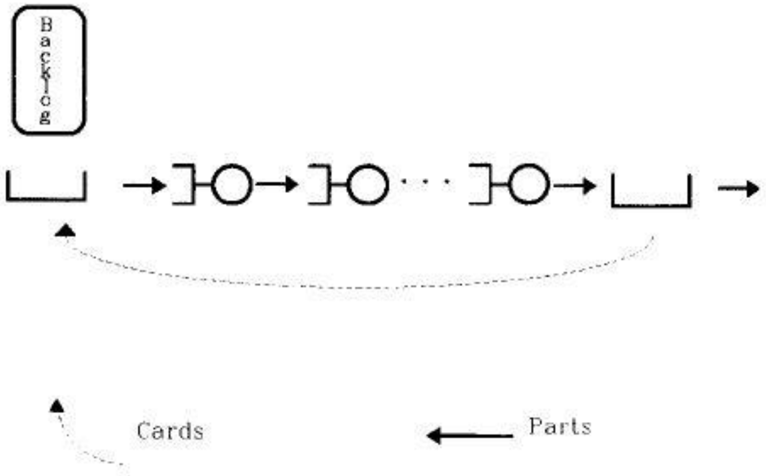


Figure 23 – CONWIP representation (Spearman, Woodruff and Hopp, 1990)

CONWIP is a continuous release method for shop floor while cards effectively regulate the flow of work; cards define the job number task and stay with the batch (containers or OKP products) through the whole length of the process. Kanban tend to control throughput while CONWIP is more focused on the production WIP even if CONWIP can provide a greater throughput than kanban (Spearman and Zazanis, 1992).As reported by (Gaury, Pierreval and Kleijnen, 2000) CONWIP is easier to model and to optimize compared to kanban; a common level of WIP in the production system is reached after the determination of optimal number of cards (Tardif and Maaseidvaag, 2001). The advantage of CONWIP is the stability preferred at the expense of a slightly higher average level of WIP since it fluctuates erratically in the push system (Stevenson, Hendry and Kingsman, 2005) while (Gaury, Pierreval and Kleijnen, 2000) point out that one disadvantage can be the inventory levels inside the system that are not controlled individually and that can lead to the storage of high inventories in front of slower machines. Further studies has been carried out by (Geraghty and Heavey, 2004) and (Yang, Fu and Yang, 2007). However, CONWIP remains strictly connected to the following different shop floor configuration:

- Pure flow shop
- General flow shop
- General job shop
- Pure job shop

The key differences among these configurations are the degree of customization and the direction of the material flow. In pure flow shop materials goes in one predefined direction through the production lines while pure job shop materials' routing is random, i.e., materials can start and finish at any work places; flow shop materials have a predominant direction but they can have some degree of freedom. The General Job Shop is defined as providing for multi-directional routing, but with a dominant flow direction (Stevenson, Hendry and Kingsman, 2005). As stated before HVLV companies normally have ETO or MTO product strategies with one of the aforementioned shop floor configuration. In fact, these manufacturing environments are characterised by HVLV features that are not ideal for a straight application of traditional LM tools (Petroni, Zammori and Marolla, 2017). As discussed earlier, CONWIP has an approach of greater applicability to the MTO industry sector than kanban and researchers agree that adopting LM in MTO job shops would be beneficial but very challenging (Slomp, Bokhorst and

Germs, 2009; Romagnoli, 2015) . Kanban has been proven to be most useful for pure flow shop while CONWIP may offer the safest generic solution; CONWIP is recommended to be used as a flow control system in a MTO environment. It is simpler to implement, presents no danger of lockup, produces good total inventory results, and has the lowest mean and variance of tardiness among flow control systems (Harrod and Kanet, 2013). Other studies reported the simulation of CONWIP in restricted part of shop floor (Khojasteh and Sato, 2015)or in a complete supply chain like (Ovalle and Marquez, 2003; Özbayrak, Papadopoulou and Samaras, 2006; Pettersen and Segerstedt, 2009) but none of the previously mentioned gave insights on the implementation of CONWIP in the shop floor of a real company. The most interesting work with a real, on-field, validation is done by (Romagnoli, 2015) that is a good starting point for the development of this research. For this reason, our research will focus on a simulative study for the design and integration of CONWIP in a general job shop MTO HVLV companies with unit-based pull system; this type of companies are frequently SMEs, with limited financial resources, that can't afford the consequences of an unsuccessful implementation of LM; the need to address the specific requirements of the MTO sector has been increasingly acknowledged in recent research literature (Stevenson, Hendry and Kingsman, 2005) and the outlook of achieving LM benefits in HVLV manufacturing environments are very promising (Thürer *et al.*, 2012, 2017).

3 - Research methodology

This chapter will focus on the main research's methods used to develop the thesis work. The first paragraph gives an introduction to these methods while the second one will deepen the case research and related literature. Simulation and the tools used for it, will be the topic of the third paragraph.

3.1 - Introduction to research methodologies

Research methodologies are one key aspects of the development of a study work. Using a systematic process in OM empirical research is mandatory to obtain credible results (Flynn, 1990) and avoid massive waste of time due to the fact that this type of research is time consuming. The main step of the process consists of:

- Theoretical foundation
- Research design
- Data collection
- Implementation
- Data analysis
- Publication

Moreover, developing a research need focus on four major element for (Crotty, 1998):

- What methods do we propose to use?
- What methodology governs our choice and use of methods?
- What theoretical perspective lies behind the methodology in question?
- What epistemology informs this theoretical perspective?

The first point focus on the tools, methods or techniques utilized to collect and analyse data in relation to the research question discussed earlier while the second one point out the reason that lies behind the utilization of a particular process or strategy and how it is related to the desired outcomes. The third point aim to give a context to the research starting from the theoretical foundation and the last one represent the knowledge needed and on which is based this context. This PhD study is based on the foundation of the literature review presented in the second chapter on the topic of LM and HVLV while the type of case research and the methods used will be analysed in the next paragraph. Case study explanation and simulations' results will be utilised to relate theory and data obtained (Bouma and Ling, 2004).

3.2- Case research

As defined earlier HVLV companies will be the main object of this study and (Voss, Tsikriktsis and Frohlich, 2002) postulate that this manufacturing environment has peculiar conditions that make case research one of the most suitable methods in OM, specifically focused in development of new theories. For example, many of the breakthrough theories and concepts in OM, like LM, have been developed through field case research (Lewis, 1998).

3.2.1 - Case study

Case study, or equivalently case research, is an empirical exploration that aim to investigate a specific phenomenon in its real context when the boundaries between phenomenon and context are not clearly evident and where multiple sources of evidence are used (Robert Yin, 2011). Normally, strategies that can be used when conducting a research are:

- Exploratory
- Descriptive
- Explanatory

The choice of a case study strategy is directly linked to some key points:

- Phenomenon and context that do not share a visible link and they are both included in the research boundaries
- Events that can not be reproduced within a controlled environment but field data's gathering is possible
- Events that are current and can be observable

- “How” or “Why” type of research questions

With the aforementioned assumption case study represent a good choice for the PhD research because with this type of strategy a wide variety of data can be created while creating a direct connection on field activity and company data collection. The empirical character of this method has some disadvantages that are frequently criticized by researchers like:

- Lack of rigor
- Replicability in different environment
- Massive production of data, partly probably useless

However, most of this assumption can be reconsidered because rigor lies in the correct choice of the research methodologies and the compliance of researcher to the procedure of the chosen methodologies. Replicability can be obtained if the research lead to a concept generalization that, within defined boundaries, can be extended to other research domains. Even though for case study is frequently common to generate a large amount of data there is a lot of methods and tools useful to identify and select the right information. Besides, the Industry 4.0 (I4.0) paradigm recently expanded enormously the focus on the production of big amount of data, called big data, that postulate the usefulness of gathering as much as possible information from the studied environment (Yin, Stecke and Li, 2018).

3.2.2 - Research design

Research design can be considered the milestone of the research work; it represents a masterplan where the researcher is guided through specific steps in order to give answers to the initial set of questions and these steps are (Robert Yin, 2011):

- Research questions' statement
- Useful data identification and collection
- Data gathering preparation
- Data gathering
- Data evaluation and analysis
- Processing conclusions and report

Even though case study is vastly acknowledged as a good research strategy, it lacks in setting some research design's standard. The development of an empirical study is complex and finding answers to the following question is required in order to achieve the project goal:

- Research design type
- Research object and questions
- Research target
- Research environment

3.2.2.1 Research design type

Case research literature agree that different types of studies can be roughly divided in two categories (Robert Yin, 2011):

- Number of cases examined
- Purposes of the studies

The number of case studies can be a single one or multiple ones; single case study is the most used and common type of research design and it can be used when this assumption are met:

- Theory testing
- Event that can not be investigated by with common methods
- Phenomenon that has not scientifically investigated yet

Single case study is well suited for the research when the case investigation is revelatory, exemplar or lead to discover uncommon research subject. Besides, single case study is more rich in details and new theories can fit in particular cases while multiple case studies are more interested in the correlation between different cases (Eisenhardt and Graebner, 2007). For this reason, multiple case design type involve two or more cases analysed within the same study in order to be a confirmation of the other one. The purpose of the studies can be mainly two; holistic analysis includes only one single unit with no sub unit so the generalization problem that has been discussed earlier could arise; the usage of this strategy is recommended only when the research is limited to the global nature of the phenomenon while embedded analysis include multiple units with sub unit on different levels. The main goal of this PhD research to find evidence of a possible LM implementation in HVLV manufacturing environment through simulation method is inherently a single case study type of research design due to this application of the real data of an Italian HVLV SME. The company has been considered as a unique ecosystem even if it is composed by multiple department and, for this reason, a holistic approach has been preferred. Investigating a general laws, or trends, rather than the particular cases is in line with the single case study design (Tsoukas, 2009). Moreover, the creation of a simulation model that aim to be generally used, with the proper modification, by other HVLV companies that share a similar MTO environment can still be possible.

3.2.2.2 Research object and question

The research object is the most important step in the case study design and it lead to the definition of the research question that has been reported in the first chapter. The researcher passes through several factors that can impact on the task like,e.g, the LR currently available for the chosen topic that sometimes can even give contrasting results and that will be the foundation of the whole research. For this reason, research questions must be carefully defined in relation to the phenomenon that has been chosen to deepen the analysis in all the possible scenarios.

3.2.2.3 Research assumption

The research assumptions are very important to limit the research and giving boundaries in which searching for data and, consequently, results. Assumption are even useful to identify the current academic knowledge and delimit the range of search. With no assumption the researcher is exposed at the risk to gather the wrong data or, even worse, gather every data.

3.2.2.4 Research environment

The research environment represents a critical element in a case study, especially in simulation; data gathering used to answer at the research questions for the building of a research theory pass from the correctness of how the research environment was initially designed and how it is coherent with the assumption that has been done.

3.2.3 – Research definition

In conclusion, Table 7 briefly summarizes all the main research definition of this PhD research in the framework illustrated in the previous paragraph:

Research	Definition
Design type	Single case study, holistic
Question	Are LM tools applicable in a HVLV environment? Which and how LM tools can be applied in HVLV environment? What are the advantages of LM in a HVLV environment?
Object	LM implementation in HVLV environment
Assumption	CONWIP enhance the company performances and improve the stability of the manufacturing line.
Environment	Alpha (Italian general job shop MTO HVLV SME)

Table 7 – PhD research definition table

3.3- Simulation

The next step in the research process has been related to identify the choice of which software was more appropriate to simulate a whole factory and especially its production process line. Simulation is a mature technology and is a powerful problem-solving tool; the flexibility of simulation modelling is a plus when compared to the restrictions imposed by mathematical formulation of a problem. Moreover, simulation is commonly used to study the practical implications of the assumptions underlying analytical models even when an analytical model can be applied to a problem. Simulation modelling can become more difficult to achieve when the researcher has to model the human behavior because a credible abstraction of human components is complex and the model's validation can be challenging. Besides, HVLV companies are the main target of this study and their manufacturing environments are recognized to be:

- Complex system
- Dynamic behaviors
- Customer demand fluctuations

Simulation refers to the activity of replicating something with suitable models; this can be an already existing reality or something that has to be designed. In the first case, the study will be on the effects of possible actions or predictable events or, in the second case, to evaluate different available design alternative.

3.3.1 - Simulation definition

Simulate implies the modeling of a process, or a system, in such a way that the model imitates the response of the real system to events that take place in time. Simulate is an empirical methodology for:

- Describing the dynamic behavior of the systems
- Validate theories and hypotheses on the model behavior
- Estimate future behavior

Simulation provides a systematic approach, explicit and efficient, to focus on the key problem; simulation needs to minimize the risk associated when critical decisions has to be taken.

3.3.2 – Simulation models

A simulation model is a representation of an object, a system or an idea into a different shape from the entity itself. These shapes normally are:

- Graphic
- Numerical
- Logical

Models are used to learn something about the real system which can not be observed or where is not be possible to have a direct experience; a model must not contain unnecessary details but only what the analyst believes it is essential for its purposes. The models which we are referring to is not used only as a tool to calculate but also as a representation of the elements that constitute the reality that we want to investigate and the relationships between them (Figure 24); the correspondence between reality and model is functional: each element of the real system are linked to a computer object. Direct experimentation can be costly and often not possible; on the other side simulation is:

- Versatile
- Low cost
- High ROI

It is possible to test quickly different design choices or alternatives through the simulation and modeling systems even of great complexity by studying the behavior and evolution in time.

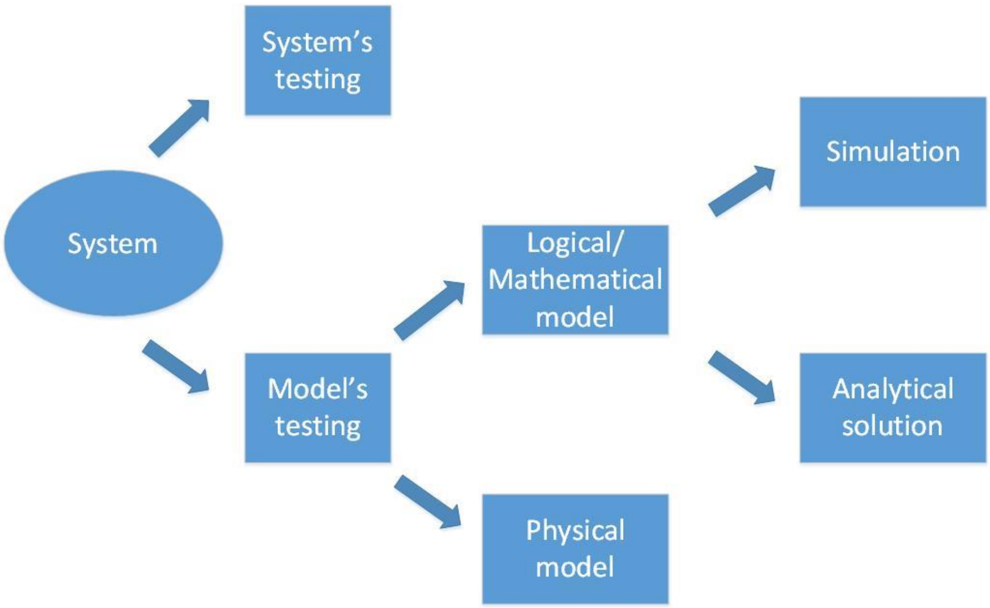


Figure 24 – Simulation system

3.3.2.1 - Simulation model definition

A simulation model is defined as an abstract representation of a real system in terms of set of states and events; it will include all the components of the system, their behavior and the possible interactions between them. A model does not necessarily consider all the details of the chosen system but must represent a simplification that emphasizes the aspects that are useful for the purposes of simulation itself. The model must be appropriate referring our objectives so the model must correctly represent the examined reality. The model also must have:

- Consistency of the system's individual components
- Consistency of results

The first point highlights the need of the individual components of the system to be consistent with the reality or the existing theory. The second point reflect the necessities that the output of the model must accurately reflect the real system. The model must allow experimentation and the testing of various hypotheses; although a real system is something objective many models can be created to represent it. For this reason, anything can be modeled in many different ways, according to which is the achievement.

3.3.2.2 -Simulation model types

The model types are:

- Icastic
- Analogic
- Logical/mathematical

The logical/mathematical model is the one used for the research; it can be represented with six features as Figure 25:

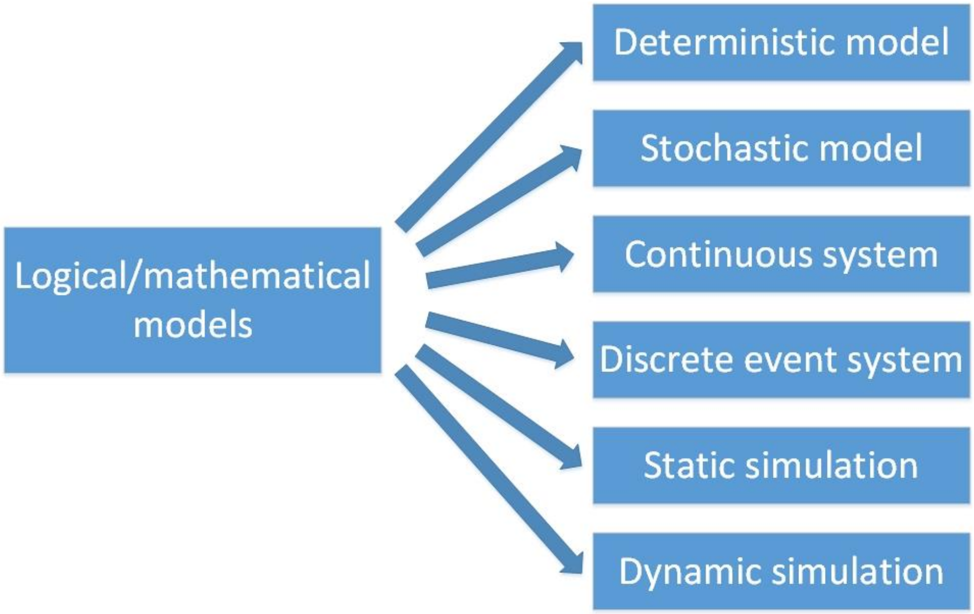


Figure 25 – Logical / mathematical model

The use of a simulation model constitutes an alternative to the realization of a system's prototype and allow to analyze and understand the behavior of a system in the presence of various alternatives and decisions. The goal of a simulation model is to identify performance indexes according to various operating conditions. It is possible to obtain the same results with analytical techniques by designing an appropriate model and resolving it through mathematical algorithms, exact or approximated; however, for complex systems, analytical techniques may introduce unacceptable simplifications. The simulation remains the unique methodology actually usable without compromises on the description of the dynamic behavior of the system.

3.3.2.2.1 - Deterministic model

Deterministic model is the one whose behavior is entirely predictable and the system is perfectly understood, then it is possible to predict precisely what will happen. Evolution in time of the model is uniquely determined by its characteristics and the initial conditions and events follow deterministic laws.

3.3.2.2.2 - Stochastic model

Stochastic model is the one whose behavior can not be entirely predicted; the times and events are affected by uncertainty and are represented by random variables.

3.3.2.2.3 - Continuous systems

Continuous systems are those systems whose status changes continuously during time; it has infinite number of states.

3.3.2.2.4 - Discrete-event systems

The discrete-event simulation model can be used as a tool of analysis to quantify and qualify, in existing systems, the effects of variations of significant parameters and to predict the performance of design-stage new systems. Discrete systems are the ones in which the state variables change only at a countable number of points in time; these points in time are the ones at which the event occurs. Although their behavior is certainly continuous such systems are most of the time operating in a discrete state; this means that their behavior can be faithfully abstracted by a succession of steady states mixed with events which make their state suddenly changing. To study these systems is therefore sufficient to observe the model's behavior at the time of event's occurrence ignoring the system's state at other moments. As reported by Nasri, "HVLV manufacturing environment are a class of dynamic systems where the behaviour can be assimilated to discrete-event dynamic systems as they are characterized by a wide variety of products using shared machines, a weak and personalized demand, relatively long processing times and frequent change over and set-up times" (Nasri, Boukezzoula and Habchi, 2012). A continuous approximation of the production flow in flow shop systems is not a suitable approach for HVLV manufacturing environment (Tamani, Boukezzoula and Habchi, 2011). Within this assumption and in relation to the wide variety of processed products, it seems promising to handle this kind of systems as job-shop type systems (Huang and Irani, 2003).

3.3.2.2.5 - Static simulation

Static simulation is built on the assumption that the state variable is in steady state, or quasi-steady state, that means that it remains constant with respect to time.

3.3.2.2.6 - Dynamic simulation

Dynamic simulation models represent the change in time of a system; in this case the performance of the model is not referred to an instantaneous state of the system. The snapshot of all the components of a system define the status of the system; event is defined as a generic cause able to change the status of the system.

3.3.3 – Simulation environment

Due to the definitions of the previous paragraphs it is now possible to define the simulation environment that best fit a HVLV manufacturing environments. These characteristics are (Table 8):

Simulation environment characteristics		
System	**Simulation**	**Model**

Discrete-event	Dynamic	Stochastic

Table 8- Simulation environment characteristics

The objective of this study is to create a stochastic discrete-event model to simulate the application of LM principles in HVLV manufacturing environment.

3.3.4 - Simulation software

Once defined, as in Table 8, the characteristics needed by the simulation software the next step is searching the one that fit best the research environment. Nowadays there is a lot of simulation software even though the number of the ones that has manufacturing simulation capabilities remains limited as shown in Table 9.

Simulation software	Software house
AnyLogic	The AnyLogic Company
Arena	Rockwell Automation
AutoMod	Applied Materials
Care pathway simulator	SAASoft Ltd.
Enterprise Dynamics	INCONTROL Simulation Solutions
ExtendSim	Imagine That Inc.
FlexSim	FlexSim Software Products, Inc.
GoldSim	GoldSim Technology Group LLC
GPSS	Various
MS4 Modeling Environment	RTSync Corporation
Tecnomatix Plant Simulation	Siemens PLM Software
ProModel	ProModel, Inc.
Simcad Pro	CreateASoft, Inc
SimEvents	MathWorks
Simio	Simio LLC.
SIMUL8	SIMUL8 Corporation
VisualSim	Mirabilis Design Inc.
WITNESS	Lanner Group Ltd.

Table 9 – Manufacturing system simulation software

The simulation software needed for the study research has to possess the following main features:

- Ability to model processes, product's flow and related information

- Advanced set of tools in order to a better comprehension of complex relationships during simulation
- Ability of deep analysis of simulated system performances in different configuration state

After a first evaluation of the software present in Table 9 and correlated to the simulation software features requested, a restricted list of the three most suitable software has been defined:

- Arena
- Anylogic
- Tecnomatix Plant simulation

Arena is one of the most well-known simulation software and easiness of use is certainly one of its key points but, on the other side, has one major problem; customization of manufacturing processes can be a hard task to achieve even with the utilization of the built-in programming language. For this reason, due to the fact that the simulation model needed to complete the study is detail-rich, Arena was not the most suitable choice. Anylogic is a new software with interesting features and this is why it was initially considered as a possible candidate; as discussed earlier, discrete-event model simulation is the best choice for our study and, besides discrete-event model, Anylogic has the ability to simulate system dynamics and agent-based model; for this reason, Anylogic is considered a multimethod modelling software. On the other side, the development of this software is still recent and it lacks in stability that is one of the most important attribute in a simulation involving multiple run of simulations. Indeed, Tecnomatix plant simulation has is major point in stability and thanks to the latest enhancements, plus a customizable environment due to a proprietary solid language programming, has gained a good reputation and making it one of the most used simulation software for manufacturing environment (Geraghty and Heavey, 2004; Marek *et al.*, 2007; Yang, Fu and Yang, 2007; Bokhorst and Slomp, 2008, 2010; Slomp, Bokhorst and Germs, 2009; Supsomboon and Vajasuvimon, 2016).

3.3.4.1 - Tecnomatix plant simulation

After a careful evaluation the chosen software is Tecnomatix Plant simulation, developed by Siemens to be used in their own facilities. Tecnomatix Plant simulation is a discrete-event simulation software that allow to create digital models of logistics systems; it can be used for the exploration of the characteristics of the systems and the optimization of their performance. These digital models allow to realize experiments and hypothetical scenarios without interfering with existing production systems or, if used in the processes of planning, before the installation of real production systems. Analysis tools like bottleneck analysis, statistics and graphs can be used to evaluate the various production scenarios. The results provided can be used as a support in decision making to afford quick and reliable decisions since the preliminary stages of planning. Tecnomatix Plant simulation can model and simulate production systems and related processes; also, it is able to optimize the flow of materials, the use of resources and logistics at all levels of the planning of the future production line up to individual specific lines for company ranging from small to big size. For this reason, tecnomatix plant simulation is the right tool for modeling an HVLV company; the models permit an evaluation of two states: the current state and the future state. Current state is the actual state of the company and it defines the starting point while future state represents the company with LM implementation. However not every tools, methods or techniques can be applied in HVLV context (Portioli-Staudacher and Tantardini, 2008); future state will include the most promising ones that LR highlighted to be applied in this specific manufacturing environments.

3.3.4.2 - Software environment

Tecnomatix plant simulation (Figure 26) is a discrete-event simulation tool capable of creating object-oriented models with hierarchal structure; the aim is to create digital models of logistic systems in order to explore a system's characteristics and to optimize its performances.

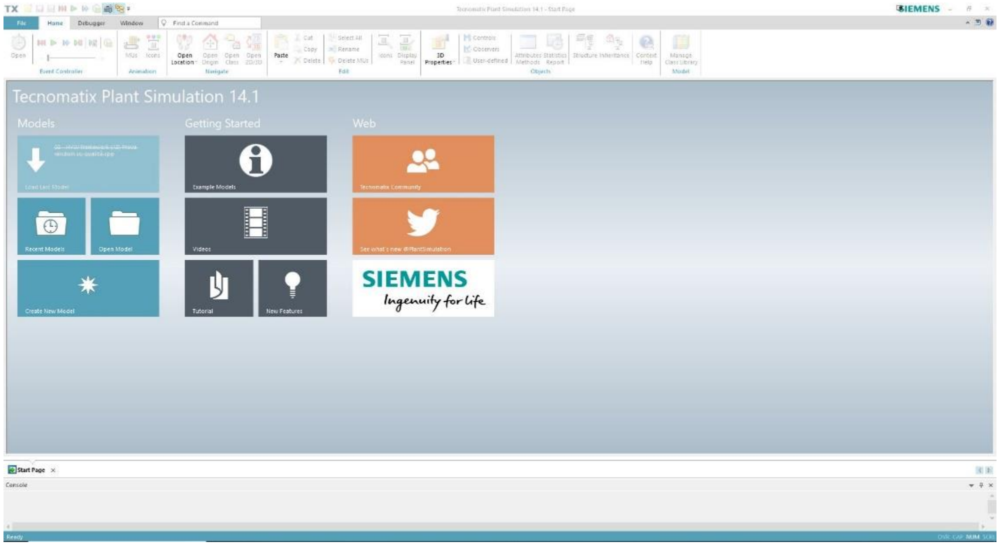


Figure 26 – Tecnomatix plant simulation

The whole model is created with predefined object present in the class library and linked together with special tool that can be chosen from the toolbox (Figure 27):

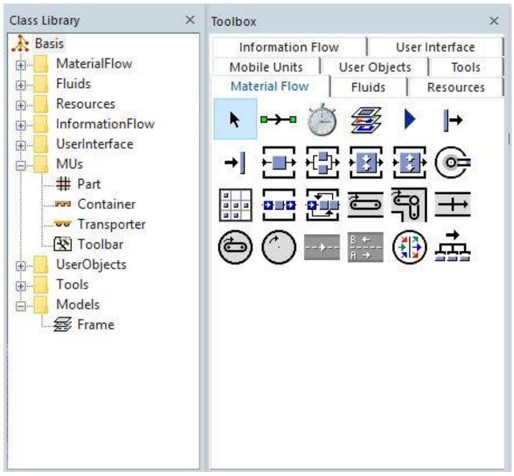
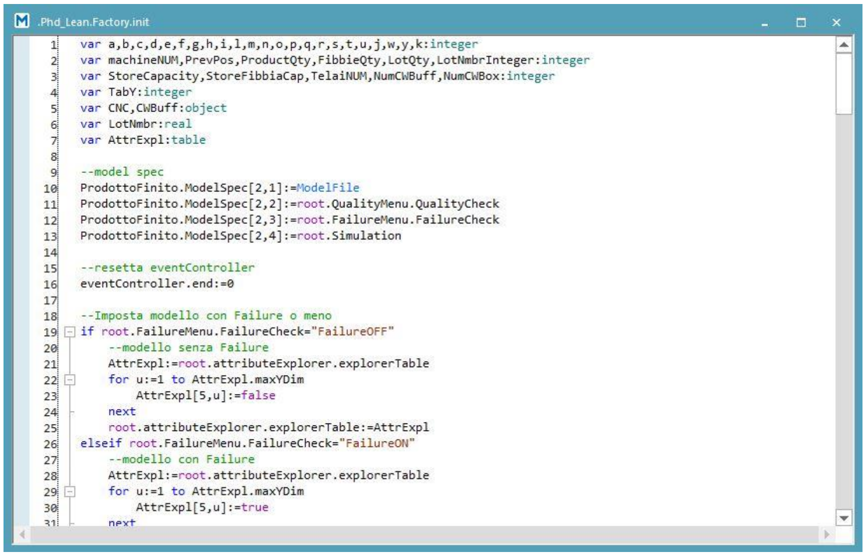


Figure 27 – Class library and toolbox

As discussed earlier, one of the key point of this simulation software is the presence of a proprietary language programming software called Simtalk (Figure 28):



```
var a,b,c,d,e,f,g,h,i,l,m,n,o,p,q,r,s,t,u,j,w,y,k:integer
var machineNUM,PrevPos,ProductQty,FibbieQty,LotQty,LotNmbrInteger:integer
var StoreCapacity,StoreFibbiaCap,TelaiNUM,NumCWBuff,NumCWBox:integer
var TabY:integer
var CNC,CWBuff:object
var LotNmbr:real
var AttrExpl:table

--model spec
ProdottoFinito.ModelSpec[2,1]:=ModelFile
ProdottoFinito.ModelSpec[2,2]:=root.QualityMenu.QualityCheck
ProdottoFinito.ModelSpec[2,3]:=root.FailureMenu.FailureCheck
ProdottoFinito.ModelSpec[2,4]:=root.Simulation

--resetta eventController
eventController.end:=0

--Imposta modello con Failure o meno
if root.FailureMenu.FailureCheck="FailureOFF"
    --modello senza Failure
    AttrExpl:=root.attributeExplorer.explorerTable
    for u:=1 to AttrExpl.maxYDim
        AttrExpl[5,u]:=false
    next
    root.attributeExplorer.explorerTable:=AttrExpl
elseif root.FailureMenu.FailureCheck="FailureON"
    --modello con Failure
    AttrExpl:=root.attributeExplorer.explorerTable
    for u:=1 to AttrExpl.maxYDim
        AttrExpl[5,u]:=true
    next
```

Figure 28 - Simtalk

Lots of simple manufacturing environments can be modelled with the standard object but often in practise is not sufficient to model realistic manufacturing environment. For this reason, to extend the capabilities of standard objects tecnomatix plant simulation provides simtalk with which it is possible to change the basic behaviour of standard objects to more complex one.

4 - Case study

This chapter will focus on the case study on which is based this study work. The first paragraph deepens the analysis of the case study related to the most important characteristics of Alpha company while the second one illustrates the Alpha simulation model and related features.

4.1– Case study analysis

As briefly discussed in the previous chapters, this PhD research is focused on a single case study of a company named Alpha. This paragraph will highlight the most important characteristics of the selected company that are fundamental for the simulation work shown in next paragraph.

4.1.1 - Alpha overview

Alpha is a company based in Tuscany operating in the high fashion industry since its foundation. The main products are metallic equipment, e.g. buckles for belts, for the most prestigious fashion brands, both Italian and foreigner. Due to the peculiar business sector, that is involving non-disclosure agreements (NDA), privacy and copyright contracts between this big companies and their suppliers, it is not possible to publish any images of the of the company nor the production line. High fashion industry is a relative small business sector that has some peculiar characteristics:

- Fast changing market
- High-margin on the product's price

The last point, both for customers and suppliers side, lead to high revenue. For this reason, suppliers must be very reactive and the opportunities for the company growth are relevant. A core competence of the company competing in this market niche is the ability to design, engineer, assemble and manage manufacturing projects (Adrodegari *et al.*, 2015). These characteristics lead to the fact that their competitive priorities are widely influenced by their competitors as well as their customers. In the last years, Alpha made high investments in new production facilities and this improvement gradually attracted new customer leading to a stronger position on the market. The company direction and the management are interested in evaluating new OM tools that can maintain and sustain the company's market position in a very restricted and competitive business sector

4.1.2 - Alpha customer demand

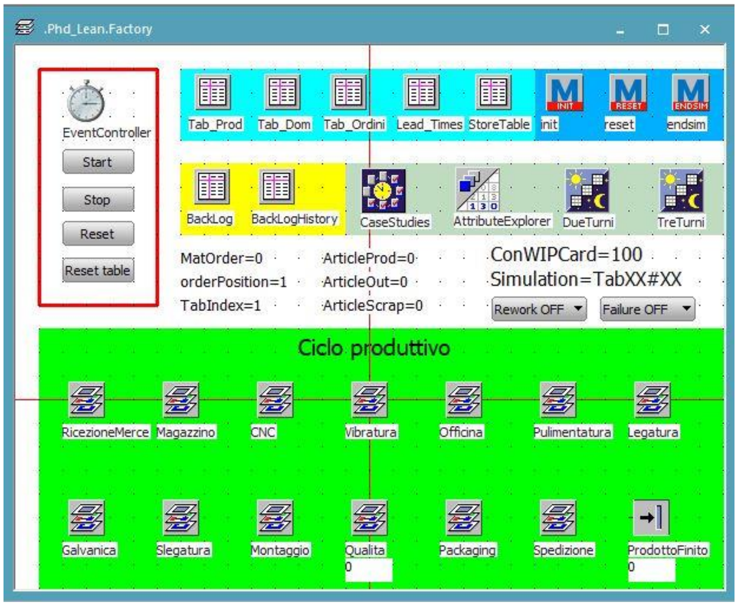
As introduced earlier, Alpha is a general job shop MTO HVLV company with a unit-based pull system. For definition, a MTO SC is a manufacturing process in which the production starts only after that the customer order has been received; this type of customer demand is highly volatile and not predictable and for this reason a production's forecast can not be afforded for the lack of demand visibility. This uncertainty hit again on the third party supplier leading to a general SC instability. In order to determine the customer demand for the simulation model usually the most common method is finding and selecting a distribution that better fit the data representing the customer demand; the main problem is that it is quite difficult to find an appropriate fitting distribution for a highly volatile customer demand with large demand variation, peculiar of the business sector; severe statistical error could invalidate the correctness of the gathered data. On the other side, a most accurate analysis of the customer demand lead to interesting results. Due to the specific sector, most of the articles requested are different from each other but they can be selected and grouped in order to obtain a class of products; similar type of articles can be clustered in order to reduce the demand variability. This clustering technique lead to identify three major types of class products that is a good approximation of the original customer demand but, for the aforementioned privacy and NDA agreements, is not possible to show the real company customer demand. In order to simulate a closer representation of reality two types of customer demand has been identified to be utilized with both the actual and future state. The first type includes several orders of the three main products while the second type includes a typical HVLV MTO manufacturing situation called rush order; rush order represent an order, or a class of orders, that has high priority and they need to be manufactured firstly. This type of orders normally leads to high instability in the whole manufacturing line causing scheduling problems. Normally, rush order are low-volume orders or even OKP.

4.1.3 - Alpha manufacturing process

The production process of metallic equipment is almost standardized for all the supplier companies and the production is divided in multiple sequential departments hereafter reported:

- Raw material entrance and control department
- Warehouse department
- Computer numerical control machines department
- Tumbling department
- Workshop department
- Polishing department
- Ligature department
- Galvanic department
- Untying department
- Assembly department
- Quality department
- Packaging and shipping department

In Figure 29 the frames representing the departments are shown:



MatOrder=0
orderPosition=1
TabIndex=1
ArticleProd=0
ArticleOut=0
ArticleScrap=0
ConWIPCard=100
Simulation=TabXX#XX

Figure 29 – Simulation model productive line frames

The production facility usually includes all of the listed department; some of the less value added tasks are demanded to third party supplier both for economical or environmental reasons; e.g., the tumbling manufacture is a low- value added task and brings several environmental problems like the waste water disposal. As discussed in paragraph 2.5, Alpha has a general job shop layout (Stevenson, Hendry and Kingsman, 2005) with multiple eight-hours shift for a working week of 5 days. Sometimes, due to the requests of customer for special events, extra working hours are needed in order to preserve the customer satisfaction. In the next paragraph a brief description of the department main task is illustrated:

4.1.3.1 - Raw material entrance and control department

The raw material entrance and control is the first process that is been carried out on the raw material entering the facility. This activity, even if it is not value added, is rather important because not only check the quality of the material but also prepare the material divided into batches for further distribution in the subsequent department.

4.1.3.2 - Warehouse department

The warehouse department is where all the material needed for the production progress is stored; its management is rather complex and a rigorous knowledge of the available products is a key factor in order to reduce the LM muda.

4.1.3.3 - Computer numerical control machines department

The computer numerical control machines department (CNC) machines department is one the two most important department in the whole manufacturing line and one of the most value added task; raw materials are utilized by several CNC machines to produce semi-finished products; these ones are collected in batch that are needed to regulate the production flow. High level of mechanical manufacturing are required for this product and several skilled operators are employed for this work.

4.1.3.4 - Tumbling department

The tumbling manufacturing process is a technique for removing and smoothing rough surfaces of printed products or products obtained with a shaving-removal process. Tumbling usually requires a specific vessel loaded with rocks of same hardness and a liquid lubricant, usually water. The vessel is connected to the main part of the tumbling machine through several springs. When powered on, the vessel starts to shake in order to impress a rotation to the object placed inside. The optimal speed of rotation depends on the size of the vessel and the desired outcome.

4.1.3.5 - Workshop department

The workshop department involves all the several and generic manual actions needed for the specific products like, e.g., threading or folding. It is one of the few departments in which there is no sequential process but it is product-dependent; for this reason, the same product can flow though this department multiple times.

4.1.3.6 - Polishing department

Polishing is the process needed to smooth the product's surface by abrasion. The polishing machine is nowadays considered as a standard and consist in two speed-controlled rotating polishing mops that, with some abrasive paste, polish the surface. This task, even at a first glance may seem an easy one and not so value added, it is crucial for a good galvanic process, as explained later, in order to achieve a good final product.

4.1.3.7 - Ligature department

After polishing, the products need to be positioned on a chassis before the further operation. Different chassis can be chosen in order to fit at best the articles' dimension and numbers.

4.1.3.8 - Galvanic department

The galvanic department is the second of the two most important departments in the production line. Galvanic is a chemical process in which a thin film of a precious material for surface coating, like gold or palladium, adhere to the surfaces of polished semi-finished products. The thickness of the film, chosen by the customer, can be customized by the operator and for this reason, due to the high price of the material used for surface coating, the galvanic department represents the most value added task of the whole production manufacturing process.

4.1.3.9 - Untying department

The untying department has a double task; the first one is removing the galvanized products and place it into special tray in which every product has a specific place with its shape. The second one is more complex; before removing the products from the chassis an initial quality check is performed. This is not an in-depth analysis but it is needed to identify the most defective products to smooth the product's progress on the next department.

4.1.3.10 - Assembly department

The assembly department is a complete handmade task composed by highly expert and trained people. As the workshop department, there is no sequential step for the product; assembly task can vary from screwing some service's screw before the galvanic through the complete assembly of a complex product, like, e.g., a lock.

4.1.3.11 - Quality department

The quality department has the key responsibility to choose the finished-products that are compatible with the quality standards of the customer. In high fashion industry, due to the high level of quality required, defects need to be restricted to very few articles per batch. If some products have some defects several choices can be faced: if a minor problem is noticed, quality department itself tries to fix it; if the problem is not solved, the products are sent back to the polishing department in order to fix it as possible. If polishing is not able to eliminate the defect, a new polishing job is done to remove the surface coating in order to galvanize the products again and, at this point, the product is marked as rework. When the rework come back at the quality department two only choices can be made; the defects has been corrected and the quality is approved or the defects are still present; in this case, the products are considered scraps and rejected. Customer's quality standards are usually military one and quality check's rules are carefully followed by the customer inspector. Quality inspection, coordinated with the customer, are frequently done by inspectors in the facility shop floor.

4.1.3.12 - Packaging and shipping department

Packaging and shipping department is the last one of the whole manufacturing process. Due to the high level of quality requested by customers, a custom packaging machines has been engineered and built to guarantee the safest packaging condition to the metallic equipment. Shipping are done on a daily basis or ad-hoc for special products.

4.2– Case study simulation model

In the next paragraph a detailed overview of the simulation model related to Alpha company will be given focusing on the main aspects and characteristics and the problems arose in order to pursuit a close approximation of the real company behavior.

4.2.1 Alpha simulation model

All the information acquired regarding Alpha's department has been used to design a simulation model with tecnomatix plant simulation. The model's design is composed by three main point:

- Design of frames representing the production departments
- Materials flow definition
- Production parameters' setup per department.

Tecnomatix plant simulation is an object-oriented software that use standard object to design and build a realistic represention of company layout. The principal types of tools utilized are inside the class library window as shown in Figure 30:

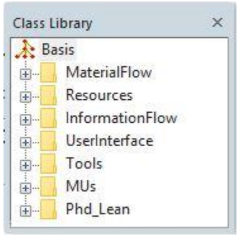
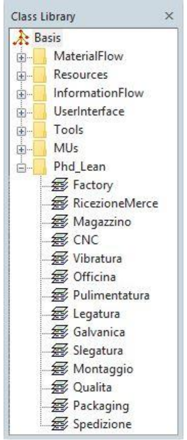


Figure 30 – Class library

Tecnomatix plant simulation uses several frames to represent each department collected in the folder Phd_Lean that represent the root of the entire model as shown in Figure 31:



Class Library

- Basis
  - MaterialFlow
  - Resources
  - InformationFlow
  - UserInterface
  - Tools
  - MUs
  - Phd_Lean
    - Factory
    - RicezioneMerce
    - Magazzino
    - CNC
    - Vibratura
    - Officina
    - Pulimentatura
    - Legatura
    - Galvanica
    - Slegatura
    - Montaggio
    - Qualita
    - Packaging
    - Spedizione

Figure 31 – Simulation models frames

The main object used to simulate the products and move it through the whole production line are mainly three, as in Figure 32, and are called:

- Mobile unit (MU)
- Container
- Transporter

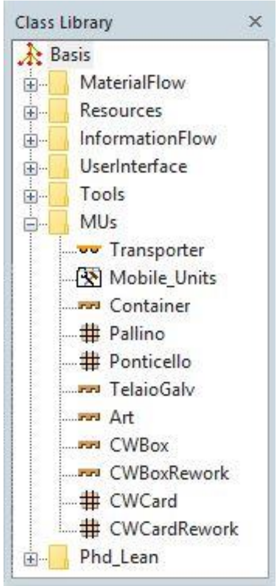


Figure 32 – Mobile units

MUs and container has been extensively utilized in order to simulate the production progress by lots. Container is a flexible object that can be used to store multiple MUs, acting like standard box for material movement, or represent a complex type of MU assembled with other parts. The main object utilized to model the work done in the department is called "SingleProc" if the task is done individually by a work center or "ParallelProc" if multiple work centres works in parallel as highlighted in Figure 33:

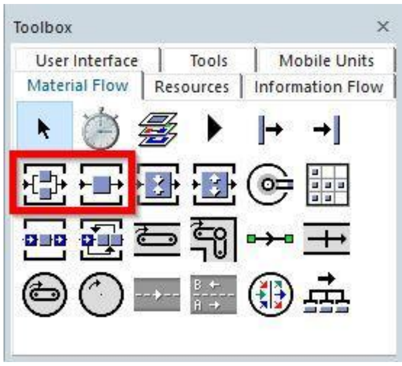
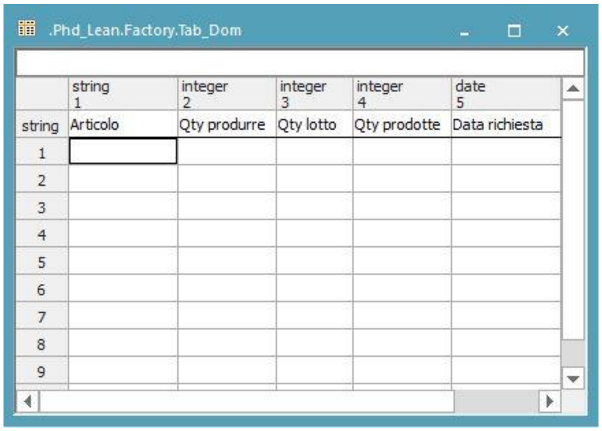


Figure 33 – Toolbox with SingleProc and ParallelProc

As discussed in paragraph 4.1.2, the cluster of grouped articles are inserted in a row where the column represent the following characteristics:

- Article's name
- Production quantity
- Lot size
- Produced quantity
- Due date

In Figure 34, the customer demand table is reported:



.Phd_Lean.Factory.Tab_Dom

	string 1	integer 2	integer 3	integer 4	date 5
string	Articolo	Qty produrre	Qty lotto	Qty prodotte	Data richiesta
1					
2					
3					
4					
5					
6					
7					
8					
9					

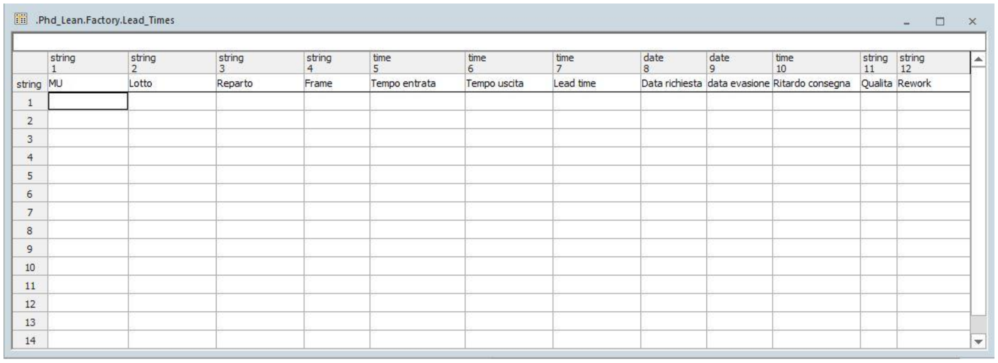
Figure 34 – Customer demand table

As discussed earlier, KPI analysis will show if the model has improved its behaviour from AS to FS and if they can be evaluated through the analysis of specific products attributes like:

- MU name
- Lot

- Department
- Frame
- Entry time
- Exit time
- Lead time
- Requested date
- Shipping date
- Delay
- Quality
- Rework

All the data collected by the several runs of simulation highlighted in the next chapter are reported in a lead times table like the one shown in Figure 35:



.Phd_Lean.Factory.Lead_Times

	string 1	string 2	string 3	string 4	time 5	time 6	time 7	date 8	date 9	time 10	string 11	string 12
string	MU	Lotto	Reparto	Frame	Tempo entrata	Tempo uscita	Lead time	Data richiesta	data evasione	Ritardo consegna	Qualita	Rework
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												

Figure 35 – Lead times table

Tecnomatix plant simulation is a software rich of features, customizable with simtalk, that allow to simulate some typical industrial characteristics; “ShiftCalendar”, for example, is very useful in order to manage different work shifts of workers of different department. As explaned in the previous paragraph, reworks and failures are two main features that has been possible to manipulate and change thanks to programming language simtalk. Hoewever, one important detail has to be highlighted: in chapter 3.3.4.2 a brief overview of simtalk (Figure 28) has been given pointing out on the fact that the standard attributes of standard object can be customized in order to represent a more realistic behaviour of the simulation model. The object can be customized through specific object called "method" that, in fact, are specific software programs wrote by a proprietary programming language; through the execution of this program the object's response to a determined state can be modified. However, even if tecnomatix plant simulation is widely used to simulate manufacturing processes, the knowledge material needed to learn to program with simtlak is very scarce. Nonetheless, Siemens itself has decided for a consultant-driven help for the company that require assistance excluding, for commercial, reason, a wide dissemination of knowledge information on this software product. For this reason, and due to the extensive changes done on the standard behaviour of objects in every department of the simulation model, learning how to correctly program the method has been a slow, complex and time-consuming task entirely accomplished during the last two years of the research study.

4.2.2 Alpha simulation model configuration

In order to evaluate the model's improvements two different states must be compared: the initial state, defined like AS, represents the as-is configuration of the company. Layout, data and all the other specific characteristics of the actual state of the company has been gathered and inserted in an AS simulation model. The other state, FS, represents the desidered Alpha manufacturing configuration in which being able to test and validate the desidered outcomes through simulation. Multiple attributes can be varied in order to reach the optimal condition and expand the numbers of results obtained.

4.2.2.1 Alpha simulation model actual state

As previously mentioned, the AS model represent the "as-is" configuration of the company before any modification of the production line; the simulation model workspace is shown in Figure 36:

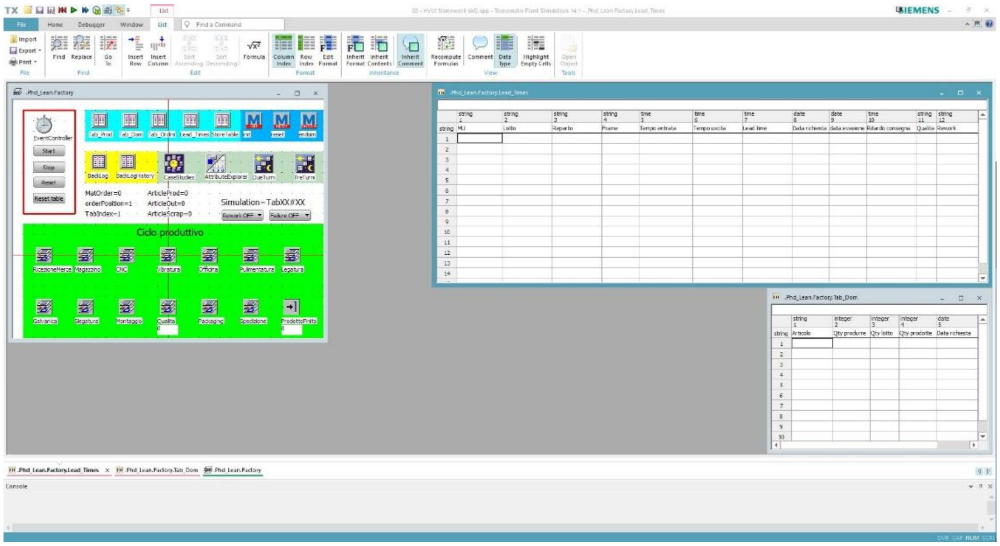


Figure 36 – Actual state

The department layout is equal to the one introduced in the previous paragraph and the main characteristics of the simulation model are summarized in Figure 37:

Attribute	Characteristics
Factory layout	Actual state
Factory shop floor type	General job shop
Departments	13
Pull mechanism	None
Work shifts	Multiple eight-hour shifts
Working day	5 days (extra for special requests)

Customer demand	As illustrated in chapter 5

Figure 37 – Actual state simulation parameters

4.2.2.2 Alpha simulation model future state

FS model highlights the company configuration for the desired outcome of LM implementation, through the adoption of CONWIP, in the manufacturing process. The simulation model workspace is shown in Figure 38:

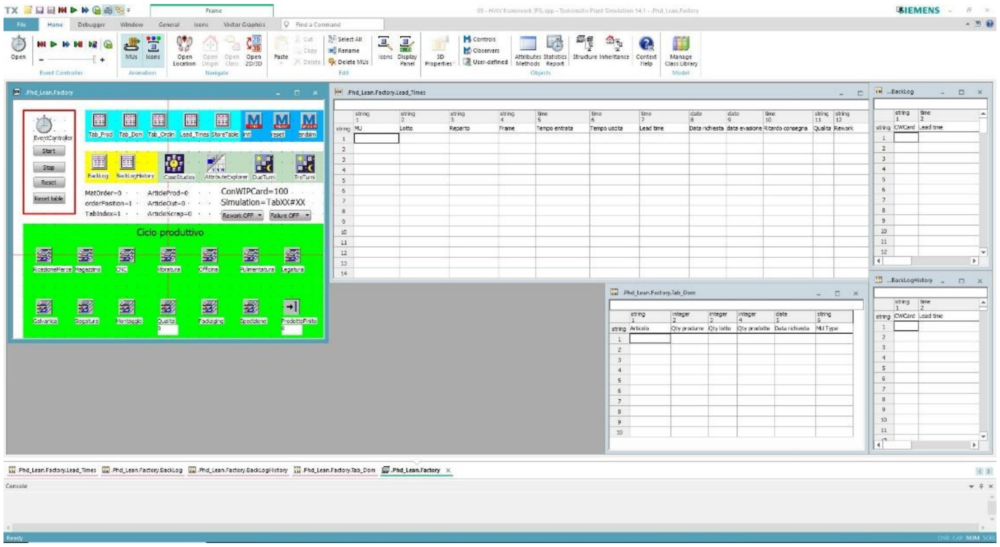
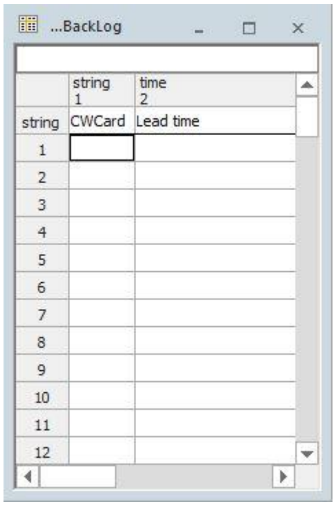


Figure 38 – Future state

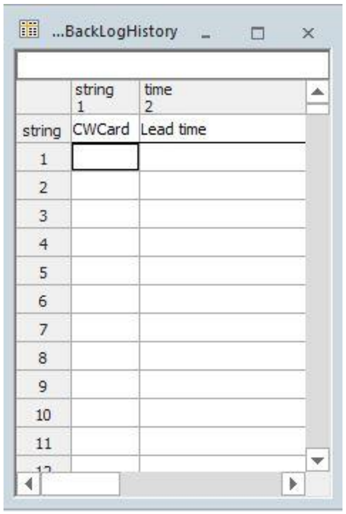
CONWIP implementation represents the key factor in order to evaluate the operational impact of this solution in the whole manufacturing line. CONWIP has been chosen due to the easiness of usage in the manufacturing environment; the main companies to whom this research is aimed are SMEs that frequently has no specific workers employed in production line's CI and, for this reason, complex transformation oftenly lead to bad results. The application of CONWIP is relativley easy and consists in applying a signal card, called "CONWIP card" (CWCard), to a visible place in the container used to move the products. The CWCard, at the beginning of the simulation, is stored in a specific warehouse and the most important characteristic, as reported by (Spearman, Woodruff and Hopp, 1990), is that the production starts only if a CWCard is available to be moved into the container. The number of used CWCards limit the maximum number of container that actually flows into the production line and this allow to limit the WIP. When a CWCard is available and enters in the production line the number of the CWCard is registered in the backlog table as Figure 39:



	string 1	time 2
string	CWCard	Lead time
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		

Figure 39 – Backlog table

The backlog shows all the CWCards that are currently in the system and when a container is shipped the CWCard is removed from the container and its lead time is recorded. The row containing the information is removed and copied in the backlog history table as in Figure 40:


...BackLogHistory

	string 1	time 2
string	CWCard	Lead time
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		

Figure 40 – Backlog history table

Finally, the CWCard is moved back in the CWCard warehouse in order to be able to initialize futher production processes. The main characteristic of the future state simulation model are summerized in Figure 41:

Attribute	Characteristics
Factory layout	Future state
Factory shop floor type	General job shop
Departments	13
Pull mechanism	CONWIP
Work shifts	Multiple eight-hour shifts
Working day	5 days (extra for special requests)
Customer demand	As illustrated in chapter 5

Figure 41 – Future state simulation parameters

5 – Simulations and results

This chapter, representing the core of the research, describes the simulation study on the lean manufacturing implementation in a HVLV context. The first paragraph illustrates the details of all the simulations while the second paragraph analyse the obtained results. The last paragraph will focus on the conclusions related to the experiments, where evidences are reported and commented.

5.1- Simulations

In this paragraph the simulations' topic related to the study research is deepened; an overview of the type of simulations is given considering all the variables of the analysed system. The main configuration parameters correlated to the different system's states are illustrated with a particular focus on the various model's attributes.

5.1.1 - Overview of simulations

The simulations' run represents the most important task for this research study; the simulation work consisted in several experiment with multiple and variable attributes. The two state are, as illustrated in the previous paragraph, following:

- Actual state
- Future state

AS and FS represents the company's macro attributes before and after the application of the CONWIP. As briefly introduced in the previous paragraph, production-related attributes are:

- Rush orders
- Failure
- Quality

Rush orders are orders that have high priority and have to be delivered in a very limited time; for all the types of companies, not only Alpha, rush orders represent a management problem due to the fact that bring instability in the whole production line and even, in the most complex industrial case, in the whole SC. Failures are main parameter acting on machines utilised in the production line; the first states, with no failures, represents the ideal state of Alpha while the second state, when failures are activated, represents the real state of the Alpha. The same happens for the quality parameter; an ideal state where all the process has no quality problem is compared to the one where two types of quality problem can arise:

- Reparation
- Rework

Reparation are minor problems that can be easily fixed with the help of adequate departments and do not involve the removal of the galvanic film. Rework, on the other side are problems where a new galvanic deposit is needed, normally after surface coating removal done by the polishing department, in order to bring back the surface product as smooth as possible.

5.1.2 – Design of experiments

Design of Experiments (DOE) is a methodology that correlates multiple process, or system, variables, in order to obtain valid results with the minimum efforts; for this reason DOE is widely used in empirical research and its importance is confirmed by many authors like (Kackar, 1989; Rowlands, Antony and Knowles, 2000; Condra, 2001; Alagumurthi, Palaniradja and Soundararajan, 2006). In order to give an overview of DOE an experiment's definition is mandatory and needed; an experiment is an investigation of a process, or a system, where it can be possible to observe the changes that occur in output data varying the input data (Figure 42). These relationships between input and output data permit to verify the effects acting on the systems and how it reacts in order to develop an effective process model.

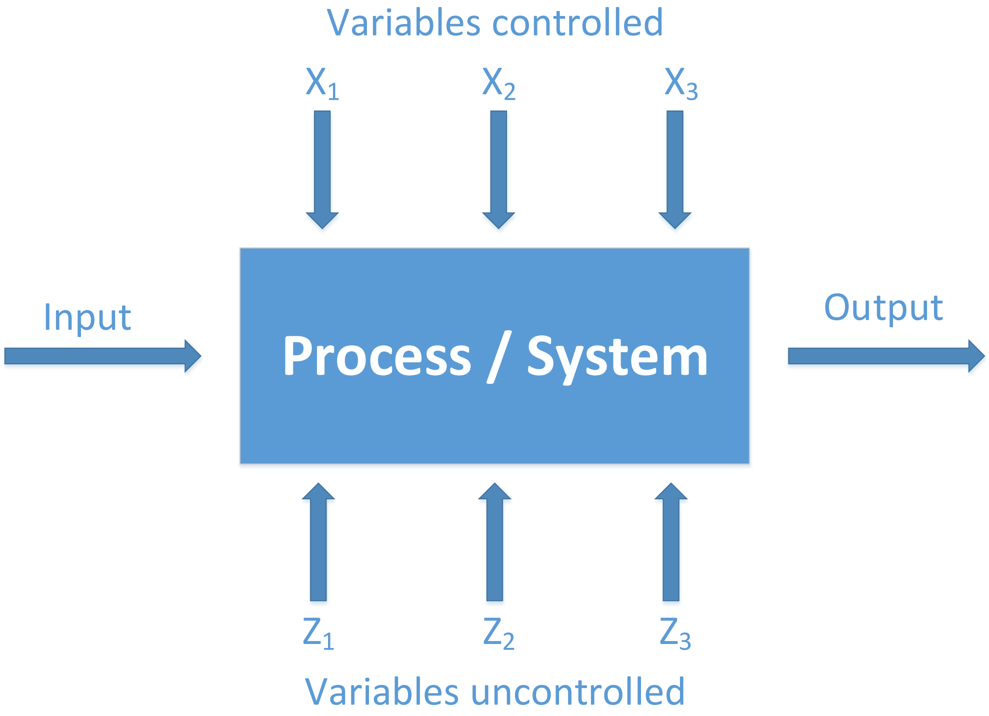


Figure 42 – Experiment definition

The first step to do a correct experiment is the determination of which variables, both the controlled X_n or the uncontrolled Z_n, have the greatest effect on the system response. Subsequently, a correct estimation of controlled variables X_n follows in order to reach:

- Acceptable output values
- Minimize output variability

Experiments have to satisfy even other parameters in order to be considered efficient. For example, experiments' results are correctly related to the research questions and therefore leads to correct conclusions. Low utilization of available resources is very important. According to (Law and Kelton, 2000) DOE is a methodology that helps to identify a specific simulation's configuration in order to obtain the desired information with a the minimum number of simulations. For this reason, DOE is an efficient and systematic approach useful to reduce the number of runs of simulation especially in the empirical research field where the number of this ones are high and each one can be time-consuming. Statistical approach is mandatory at the designing stage of the experiments; significant conclusions gathered from robust results data are obtained when the input values are not suffering from errors due to high variation. Statistical robustness can be reached through the adoption of the following principles:

- Reproducibility
- Randomizing
- Block Execution

Reproducibility is related to the repetition of the experiment with the same input data in order to obtain a more precise result getting an average sample and estimate the experimental error through the sample standard deviation. Randomizing means doing experiments in a random order to be able to decouple the conditions of a run from each other and avoiding the introduction of bias. Block execution means to group together experiments carried out with similar external factors in order to reduce the variability and improve accuracy.

5.2- Experiments

Experiments is the main topic investigated in this paragraph; an overview of the experiments that have been carried out is illustrated highlighting the whole variables needed to correctly define the experiments. An in-depth analysis of the customer demand follows in the second paragraph while AS and FS model's configurations is examined in the third and fourth paragraph. A study on the optimal parameter, needed to reduce the simulation effort and delimit the experiment boundaries, is presented in the fifth paragraph. The experiment results are shown in a results table in the last paragraph and correlated with the research questions in the next chapter.

5.2.1 - Overview of experiments

An experiment is defined as a procedure executed to test a hypothesis in order to support, refute or validate it. Insight of cause-and-effect when a variable is modified, by the outcome observation, is the main reason of conducting experiments and gathering data from it. As introduced in the previous paragraphs, three main specific attributes are relevant for their impact on Alpha company and are:

- Rework
- Rush order
- Failure

The factors investigated are three while the possible states are two; a simple combinatorial problem that lead to a possible combination of 8 cases as illustrated in Table 1Table 10:

Rework	Rush Order	Failure
no	no	no

no	no	yes
yes	no	no
yes	no	yes
no	yes	no
no	yes	yes
yes	yes	no
yes	yes	yes

Table 10 – Parameters configuration

5.2.2 – Customer demand

The customer demand is a key factor for the experiments task. As briefly introduced in the previous paragraphs and chapters, the four most representative and characteristics customer demand have been obtained by the analysation of the historical data of Alpha company. As a consequence of the particular business sector there is no possibility to extract a repetitive pattern grouping the same articles. The only possibility in order to obtain a customer order that can be adherent to a real Alpha one is to identify the articles that share the same characteristics in the production process and group it together. By doing so, three major type of groups of articles emerged, named "a","b" and "c", as illustrated in the next paragraphs. As previously pointed out, due to NDA and privacy agreements between Alpha company and its customer it is not possible to show the historical and original productions plan on which the following customer orders are based.

5.2.2.1 – Customer order #1

Customer order #1 (CO1), as shown in Table 11, represent the most standard production requests that fit, approximately, one real working month of Alpha company. Two separated lots of each articles have been considered in order to give the best approximation of the real orders and the lot quantity, that is fundamental in order to test the CONWIP performance in the FS model, has been adopted by looking at the real mean value of lot quantity and adjusted, where needed, for the real production necessities. No rush orders are considered for this specific order.

Article	Article quantity	Lot quantity
a1	1800	200
a2	2200	250
b1	3500	400
b2	3200	350
c1	3800	200
c2	4100	200

Table 11 – Customer order #1

5.2.2.2 – Customer order #2

Customer order #2 (CO2), as shown in Table 12, share the same principles of CO1 but, in order to evaluate different cases highlighted in the real historical data of production planning and as previously introduced, four rush orders, named “r”, have been added and their production priority have been carefully evaluated in relation with the aforementioned historical production plans. The rush orders lot quantities are data collected by in-field observations.

Article	Article quantity	Lot quantity
a1	1800	200
r1	380	50
a2	2200	250
b1	3500	400

r2	420	50
r3	660	100
b2	3200	350
c1	3800	200
r4	620	100
c2	4100	200

Table 12 - Customer order #2

5.2.2.3 - Customer order #3

Customer order #3 (CO3), as shown in Table 13, is a variation of CO2 in order to test different experiment conditions.

Article	Article quantity	Lot quantity
a1	1800	200
r1	270	50
a2	2200	250
r2	330	50
b1	2700	310
b2	3800	200
c1	1700	200
r3	530	100
r4	480	50
c2	4100	200

Table 13 - Customer order #3

5.2.2.4 - Customer order #4

Customer order #4 (CO4), as shown in Table 14, share the same principles of CO2 and CO3 and represent the last variation of the customer demand object of this research.

Article	Article quantity	Lot quantity
a1	1800	200
r1	130	50
a2	2200	250
b1	3500	400
r2	160	50
r3	250	50
b2	3200	350
r4	230	50
c1	3800	200
c2	4100	200

Table 14 - Customer order #4

5.2.3 – Actual state

Considering all the information gathered from the previous paragraphs and chapters, the simulation model characteristics of AS are defined in Table 15:

CONWIP	Customer demand	Parameters
No	CO1	Rework
	CO2	Rush order
	CO3	Failure
	CO4	

Table 15 – Actual state characteristics table

Lastly, the AS table utilized for experiments embody four possible configurations inherited from the customer demand for a total of sixteen experiments, as shown in Table 16:

Config.	CONWIP	Client order	Exp. #	Rework	Rush Order	Failure
1	No	CO1	1	no	no	no

			2	no	no	yes
			3	yes	no	no
			4	yes	no	yes
2	No	CO2	5	no	yes	no
			6	no	yes	yes
			7	yes	yes	no
			8	yes	yes	yes
3	No	CO3	9	no	yes	no
			10	no	yes	yes
			11	yes	yes	no
			12	yes	yes	yes
4	No	CO4	13	no	yes	no
			14	no	yes	yes
			15	yes	yes	no
			16	yes	yes	yes

Table 16 – Actual state table

5.2.4 - Future state

As defined for AS in the previous paragraph, the simulation model characteristics of AS are defined in Table 17:

CONWIP	Customer demand	Parameters
Yes	CO1	Rework
	CO2	Rush order
	CO3	Failure
	CO4	

Table 17 - Future state characteristics table

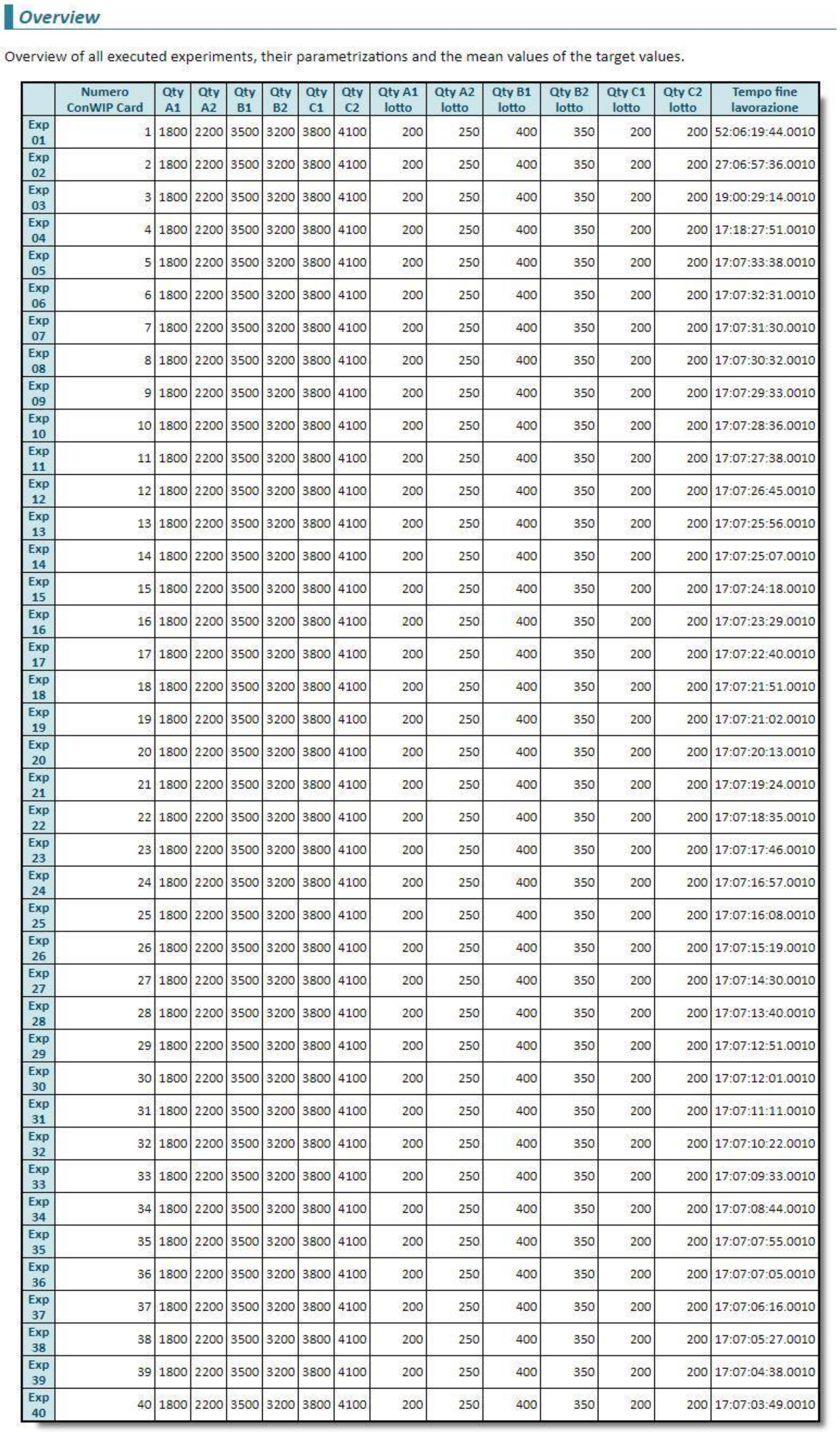
The FS table utilized for experiments embody four possible configurations inherited from the customer demand for a total of sixteen experiments, as shown in Table 18:

Config.	CONWIP	Client order	Exp. #	Rework	Rush Order	Failure
5	Yes	CO1	17	no	no	no
			18	no	no	yes
			19	yes	no	no
			20	yes	no	yes
6	Yes	CO2	21	no	yes	no
			22	no	yes	yes
			23	yes	yes	no
			24	yes	yes	yes
7	Yes	CO3	25	no	yes	no
			26	no	yes	yes
			27	yes	yes	no
			28	yes	yes	yes
8	Yes	CO4	29	no	yes	no
			30	no	yes	yes
			31	yes	yes	no
			32	yes	yes	yes

Table 18 – Future state table

5.2.5 – Future state simulation optimization

FS's main features is the implementation of CONWIP in the production line; CWCard, as introduced in the previous paragraphs, are the ones that enable the entrance of the semi-finished materials in the shop floor; the main goal of this research is to find the best number of CWCard in order to smooth as possible the production and consequently the lead times. In order to apply the DOE's principles, the number of simulations must be kept as low as possible to reduce at the minimum the simulation effort, both for resources and time available. Besides, some CWCard simulation have less, or no, interest for the objective of this research like, e.g., the simulation with one CWCard; in real world, it means to have just one box with a fixed amount of articles flowing through the shop floor and obviously that is not a real industrial case. For this reason, for FS model, have been carried out some random simulation in order to identify which is the best range of CWCard to use in order to reduce at minimum the number of simulation while having a valid data gathering from the results. In Figure 43 the results of experiment 17 is highlighted. The latest column shows the total time needed to deliver the customer order called makespan; makespan is continuously reduced as CWCard number grow up but after some iteration this increases tend to stabilize. Between experiment twenty and experiment forty the makespan difference is of only seventeen minutes on a total simulation time of more than seventeen hours. On the other side, before experiment number ten, there is no industrial relevance in the results obtained and the convergence to a CWCard number that is significant for the study is confirmed even by other random simulation test done for the AS model state. For this reason, all the simulation will be executed between the range of ten and twenty CWCard.



Overview

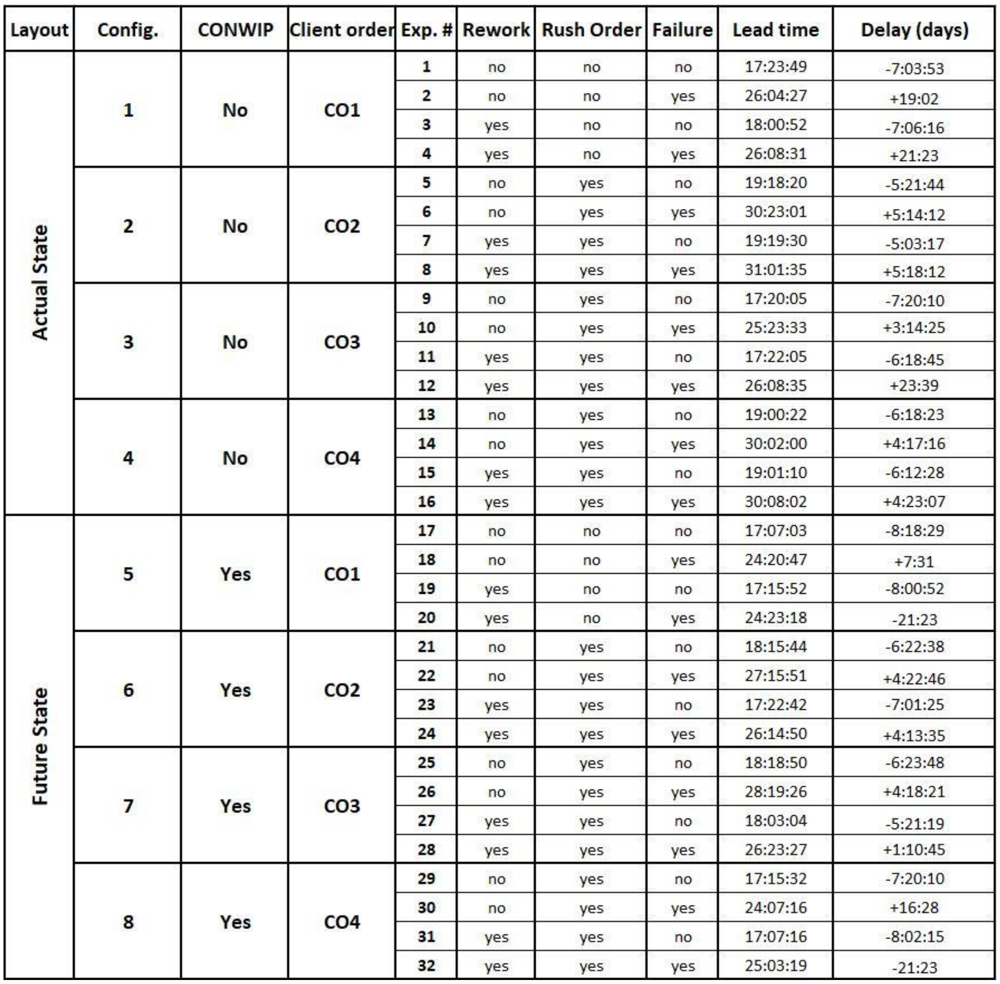
Overview of all executed experiments, their parametrizations and the mean values of the target values.

	Numero ConWIP Card	Qty A1	Qty A2	Qty B1	Qty B2	Qty C1	Qty C2	Qty A1 lotto	Qty A2 lotto	Qty B1 lotto	Qty B2 lotto	Qty C1 lotto	Qty C2 lotto	Tempo fine lavorazione
Exp 01	1	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	52:06:19:44.0010
Exp 02	2	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	27:06:57:36.0010
Exp 03	3	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	19:00:29:14.0010
Exp 04	4	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:18:27:51.0010
Exp 05	5	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:33:38.0010
Exp 06	6	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:32:31.0010
Exp 07	7	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:31:30.0010
Exp 08	8	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:30:32.0010
Exp 09	9	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:29:33.0010
Exp 10	10	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:28:36.0010
Exp 11	11	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:27:38.0010
Exp 12	12	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:26:45.0010
Exp 13	13	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:25:56.0010
Exp 14	14	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:25:07.0010
Exp 15	15	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:24:18.0010
Exp 16	16	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:23:29.0010
Exp 17	17	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:22:40.0010
Exp 18	18	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:21:51.0010
Exp 19	19	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:21:02.0010
Exp 20	20	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:20:13.0010
Exp 21	21	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:19:24.0010
Exp 22	22	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:18:35.0010
Exp 23	23	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:17:46.0010
Exp 24	24	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:16:57.0010
Exp 25	25	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:16:08.0010
Exp 26	26	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:15:19.0010
Exp 27	27	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:14:30.0010
Exp 28	28	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:13:40.0010
Exp 29	29	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:12:51.0010
Exp 30	30	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:12:01.0010
Exp 31	31	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:11:11.0010
Exp 32	32	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:10:22.0010
Exp 33	33	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:09:33.0010
Exp 34	34	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:08:44.0010
Exp 35	35	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:07:55.0010
Exp 36	36	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:07:05.0010
Exp 37	37	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:06:16.0010
Exp 38	38	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:05:27.0010
Exp 39	39	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:04:38.0010
Exp 40	40	1800	2200	3500	3200	3800	4100	200	250	400	350	200	200	17:07:03:49.0010

Figure 43 – Simulation optimization

5.2.6 – Experiment results

The results obtained from the simulations illustrated in Table 16 and Table 18 are reported in the following Figure 44:



Layout	Config.	CONWIP	Client order	Exp. #	Rework	Rush Order	Failure	Lead time	Delay (days)
Actual State	1	No	CO1	1	no	no	no	17:23:49	-7:03:53
				2	no	no	yes	26:04:27	+19:02
				3	yes	no	no	18:00:52	-7:06:16
				4	yes	no	yes	26:08:31	+21:23
	2	No	CO2	5	no	yes	no	19:18:20	-5:21:44
				6	no	yes	yes	30:23:01	+5:14:12
				7	yes	yes	no	19:19:30	-5:03:17
				8	yes	yes	yes	31:01:35	+5:18:12
	3	No	CO3	9	no	yes	no	17:20:05	-7:20:10
				10	no	yes	yes	25:23:33	+3:14:25
				11	yes	yes	no	17:22:05	-6:18:45
				12	yes	yes	yes	26:08:35	+23:39
	4	No	CO4	13	no	yes	no	19:00:22	-6:18:23
				14	no	yes	yes	30:02:00	+4:17:16
				15	yes	yes	no	19:01:10	-6:12:28
				16	yes	yes	yes	30:08:02	+4:23:07
Future State	5	Yes	CO1	17	no	no	no	17:07:03	-8:18:29
				18	no	no	yes	24:20:47	+7:31
				19	yes	no	no	17:15:52	-8:00:52
				20	yes	no	yes	24:23:18	-21:23
	6	Yes	CO2	21	no	yes	no	18:15:44	-6:22:38
				22	no	yes	yes	27:15:51	+4:22:46
				23	yes	yes	no	17:22:42	-7:01:25
				24	yes	yes	yes	26:14:50	+4:13:35
	7	Yes	CO3	25	no	yes	no	18:18:50	-6:23:48
				26	no	yes	yes	28:19:26	+4:18:21
				27	yes	yes	no	18:03:04	-5:21:19
				28	yes	yes	yes	26:23:27	+1:10:45
	8	Yes	CO4	29	no	yes	no	17:15:32	-7:20:10
				30	no	yes	yes	24:07:16	+16:28
				31	yes	yes	no	17:07:16	-8:02:15
				32	yes	yes	yes	25:03:19	-21:23

Figure 44 – Results table

5.3- Results

The mail goal of this doctoral research is about discovering if a useful LM implementation in HVLV environments companies, whose impact on operational performance has been covered in the LR chapter, can be achieved and which are the entities of this new production paradigm. The results of the simulation shown in Figure 44 highlight the potential of this approach. The single case study, as previously discussed and stated by (Yin, 2009), does not interfere in obtaining new general considerations and can help in finding insights and operational improvements for other companies sharing the same manufacturing environment with a similar SC. In the next paragraphs, answers to the research question highlighted in chapter 1 are discussed.

5.3.1 Are LM tools applicable in a HVLV environment?

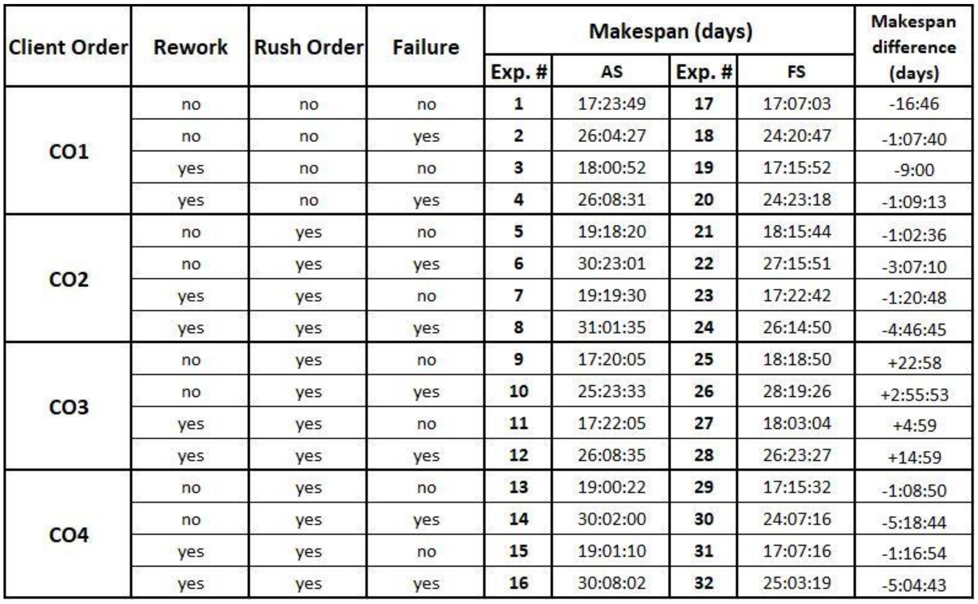
As analysed in chapter 2 and as stated by (Slomp, Bokhorst and Germs, 2009) some LM tools can be implemented in an HVLV environment and can be compatible to type of SC related to that manufacturing environment. However, not all this tools and methodologies that are compatible can be applied with a straight-forward approach but they need further modification that sometimes are very deeply. As stated by (Portioli-Staudacher and Tantardini, 2008), some of them can not be implemented at all and remains applicable strictly to LVHV environments. The present study work corroborates the assumption of the work of (Bokhorst and Slomp, 2010) highlighting the fact that some LM tools, or modified ones, can be applicable to HVLV environments. As reported in paragraph 3.2.3, the main characteristics of Alpha are being an Italian general job shop MTO HVLV SME type of company and the research has been conducted as a single case study. According to (Yin, 2009), further implementation can be extended to similar case study utilising the methods and results obtained by this research work.

5.3.2 Which and how LM tools can be applied in HVLV environment?

LM application in HVLV is a relatively new research field and, as highlighted in LR, not so many papers deepen this topic. As stated by (Buetfering *et al.*, 2016) HVLV environments gains interests and the implementation of LM in it represents a gap in research. CONWIP, as highlighted in LR, has gained attention as an extension of kanban for HVLV environment by (Spearman, Woodruff and Hopp, 1990) but further analysis are scarce in literature: A software simulations of a hypothetical production line has been done by (Germs and Riezebos, 2010) or (Harrod and Kanet, 2013) while applications on partial manufacturing line has been highlighted in the paper of (Bokhorst and Slomp, 2010). A real in-field application work, with similar manufacturing environment, has been done by (Romagnoli, 2015) and represent a good comparison for this research work. As for (Romagnoli, 2015) findings, the implementation of CONWIP in this real manufacturing environment has led to an increase of operational performance confirming that CONWIP is a good enhancement of kanban in this specific sector. However, a key point is represented by the customer order; four types of the most common customer order has been derived from the analysis of the original production plan of Alpha company and utilised for simulating the manufacturing line behaviour. The results reported in Figure 45and Figure 46 point out that FS, with the implementation of CONWIP, outperforms the AS of Alpha where no push system are used except when CO3 is applied to the model where the results shows a slight disadvantage of CONWIP application. For this reason, the research suggests that a careful evaluation of the customer demand is one of the most critical factor in order to successfully implement the CONWIP as a push system for HVLV companies. Further studies could deepen the relationships between a given customer demand and a successful LM implementation in HVLV environment.

5.3.3 What are the advantages of LM in a HVLV environment?

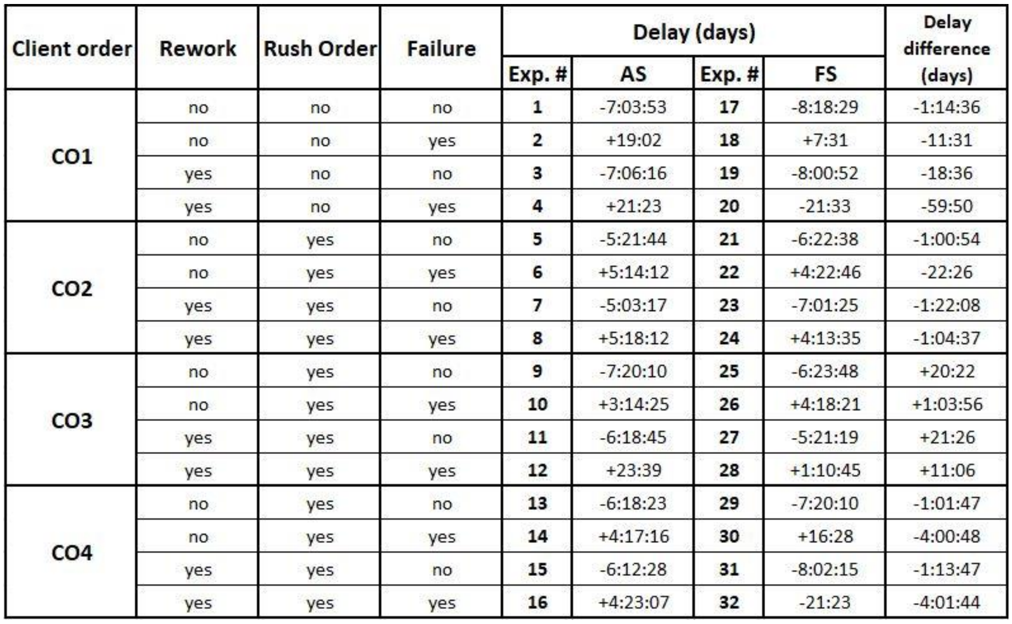
Improvements achievable by the applications of LM in a manufacturing system is well known and documented. However, as analyzed in the LR and stated in the previous paragraphs, LM ecosystem of tools and methods are not easily extensible to HVLV environments; for this reason, finding and implementing an already existent LM tools, or an HVLV modified ones, that could extend the benefits of LM even to this specific manufacturing environment is mandatory in order to increase operational performances for the HVLV companies. In Figure 45 the makespan comparison between FS and AS are reported:



Client Order	Rework	Rush Order	Failure	Makespan (days)				Makespan difference (days)
				Exp. #	AS	Exp. #	FS	
CO1	no	no	no	**1**	17:23:49	**17**	17:07:03	-16:46
	no	no	yes	**2**	26:04:27	**18**	24:20:47	-1:07:40
	yes	no	no	**3**	18:00:52	**19**	17:15:52	-9:00
	yes	no	yes	**4**	26:08:31	**20**	24:23:18	-1:09:13
CO2	no	yes	no	**5**	19:18:20	**21**	18:15:44	-1:02:36
	no	yes	yes	**6**	30:23:01	**22**	27:15:51	-3:07:10
	yes	yes	no	**7**	19:19:30	**23**	17:22:42	-1:20:48
	yes	yes	yes	**8**	31:01:35	**24**	26:14:50	-4:46:45
CO3	no	yes	no	**9**	17:20:05	**25**	18:18:50	+22:58
	no	yes	yes	**10**	25:23:33	**26**	28:19:26	+2:55:53
	yes	yes	no	**11**	17:22:05	**27**	18:03:04	+4:59
	yes	yes	yes	**12**	26:08:35	**28**	26:23:27	+14:59
CO4	no	yes	no	**13**	19:00:22	**29**	17:15:32	-1:08:50
	no	yes	yes	**14**	30:02:00	**30**	24:07:16	-5:18:44
	yes	yes	no	**15**	19:01:10	**31**	17:07:16	-1:16:54
	yes	yes	yes	**16**	30:08:02	**32**	25:03:19	-5:04:43

Figure 45 – FS-AS makespan comparison

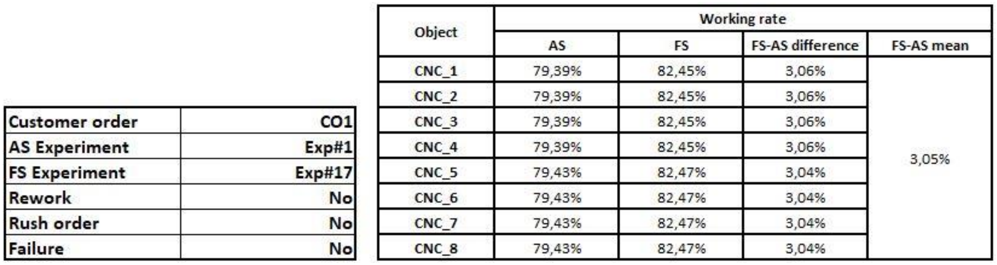
The first results obtained are related to the analysis of the difference of makespans, in days, between FS and AS models. CO1 (Table 11) FS model's has better results on all the possible configuration, with a mean value of less than one day in advance on delivery date, respect to the AS one. Even CO2 (Table 12) FS model's shows better performance than AS ones, even though results vary greatly depending on the parameters simulated. CO3 (Table 13) FS model's shows weaker performances than AS model; further investigation on this topic can be done as a starting point for other research work studies. CO4, reported in Table 14, highlights the same irregular behaviour between different simulation parameters. The comparison between the makespan difference of FS and AS models highlight better performances for CONWIP except for the case with CO3 that deserves further investigation. In Figure 46 the comparison of delays between AS and FS models, expressed in days, are listed:



Client order	Rework	Rush Order	Failure	Delay (days)				Delay difference (days)
				Exp. #	AS	Exp. #	FS	
CO1	no	no	no	**1**	-7:03:53	**17**	-8:18:29	-1:14:36
	no	no	yes	**2**	+19:02	**18**	+7:31	-11:31
	yes	no	no	**3**	-7:06:16	**19**	-8:00:52	-18:36
	yes	no	yes	**4**	+21:23	**20**	-21:33	-59:50
CO2	no	yes	no	**5**	-5:21:44	**21**	-6:22:38	-1:00:54
	no	yes	yes	**6**	+5:14:12	**22**	+4:22:46	-22:26
	yes	yes	no	**7**	-5:03:17	**23**	-7:01:25	-1:22:08
	yes	yes	yes	**8**	+5:18:12	**24**	+4:13:35	-1:04:37
CO3	no	yes	no	**9**	-7:20:10	**25**	-6:23:48	+20:22
	no	yes	yes	**10**	+3:14:25	**26**	+4:18:21	+1:03:56
	yes	yes	no	**11**	-6:18:45	**27**	-5:21:19	+21:26
	yes	yes	yes	**12**	+23:39	**28**	+1:10:45	+11:06
CO4	no	yes	no	**13**	-6:18:23	**29**	-7:20:10	-1:01:47
	no	yes	yes	**14**	+4:17:16	**30**	+16:28	-4:00:48
	yes	yes	no	**15**	-6:12:28	**31**	-8:02:15	-1:13:47
	yes	yes	yes	**16**	+4:23:07	**32**	-21:23	-4:01:44

Figure 46 – FS-AS delay comparison

The subsequent analysis aims to find evidence of CONWIP performance not analysing the makespan but focusing on the delays calculated between the desired delivery date and the effective, simulated, delivery date. CO1 (Table 11) FS model's has better results on all the possible configuration, with a mean value of roughly one day in advance on the difference of delivery date, respect to the AS one. CO2, shown in Table 12, FS model's shows better performance of more than one day in advance. CO3 (Table 13) FS model's shows weaker performances when compared to the AS ones. As previously discussed, further investigation on this topic can be done as a starting point for other research work studies. CO4, reported in Table 14, highlights an irregular behaviour between the various configuration even though the FS model outperform the AS one. The comparison between FS and AS models difference of delays highlight better performances for CONWIP except for the case with CO3 that deserves further investigation. The previous analysis focused on the KPI relative to WIP, lead times and delays while the following ones highlights the resource utilization. However, this thesis work is focusing on Alpha company that is in the high fashion business sector; one of the most critical department of this type of companies is the CNC one where the needs of having the machine working for the maximum of the production time available is mandatory in order to obtain good business performances. An in-depth analysis, related to the four type of customer order, of the difference of resource utilization between FS and AS models follows:

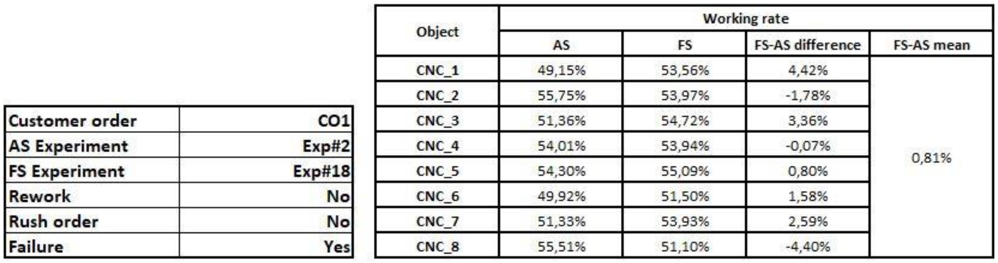


Customer order	**CO1**
AS Experiment	**Exp#1**
FS Experiment	**Exp#17**
Rework	**No**
Rush order	**No**
Failure	**No**

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	79,39%	82,45%	3,06%	3,05%
CNC_2	79,39%	82,45%	3,06%	
CNC_3	79,39%	82,45%	3,06%	
CNC_4	79,39%	82,45%	3,06%	
CNC_5	79,43%	82,47%	3,04%	
CNC_6	79,43%	82,47%	3,04%	
CNC_7	79,43%	82,47%	3,04%	
CNC_8	79,43%	82,47%	3,04%	

Figure 47 – CO1 Experiment#1-17 comparison

In relation to CO1 (Table 11) and Figure 47, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 3,05%.

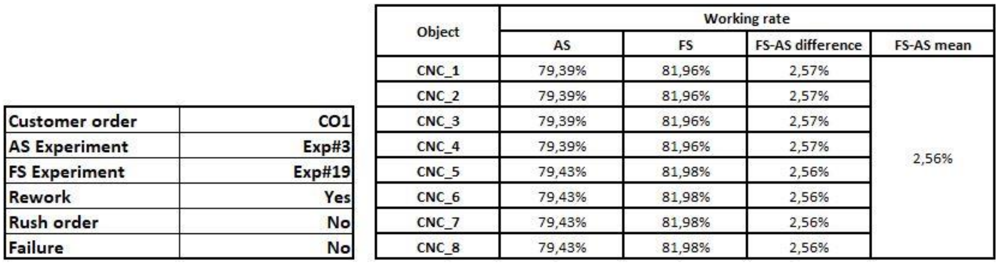


Customer order	CO1
AS Experiment	Exp#2
FS Experiment	Exp#18
Rework	No
Rush order	No
Failure	Yes

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	49,15%	53,56%	4,42%	0,81%
CNC_2	55,75%	53,97%	-1,78%	
CNC_3	51,36%	54,72%	3,36%	
CNC_4	54,01%	53,94%	-0,07%	
CNC_5	54,30%	55,09%	0,80%	
CNC_6	49,92%	51,50%	1,58%	
CNC_7	51,33%	53,93%	2,59%	
CNC_8	55,51%	51,10%	-4,40%	

Figure 48 - CO1 Experiment#2-18 comparison

In relation to CO1 (Table 11) and Figure 48, the FS model's shows irregular values of performances related to all the CNC machines, even though, with a mean value of difference between FS and AS models of 0,81%, FS model has a slight advantage.

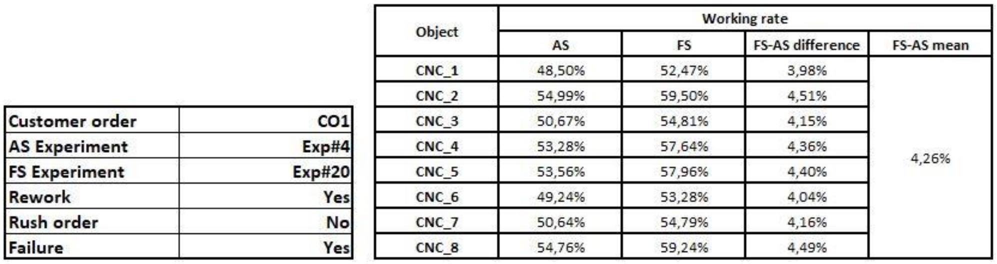


Customer order	CO1
AS Experiment	Exp#3
FS Experiment	Exp#19
Rework	Yes
Rush order	No
Failure	No

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	79,39%	81,96%	2,57%	2,56%
CNC_2	79,39%	81,96%	2,57%	
CNC_3	79,39%	81,96%	2,57%	
CNC_4	79,39%	81,96%	2,57%	
CNC_5	79,43%	81,98%	2,56%	
CNC_6	79,43%	81,98%	2,56%	
CNC_7	79,43%	81,98%	2,56%	
CNC_8	79,43%	81,98%	2,56%	

Figure 49 - CO1 Experiment#3-19 comparison

In relation to CO1 (Table 11) and Figure 49, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 2,56%.

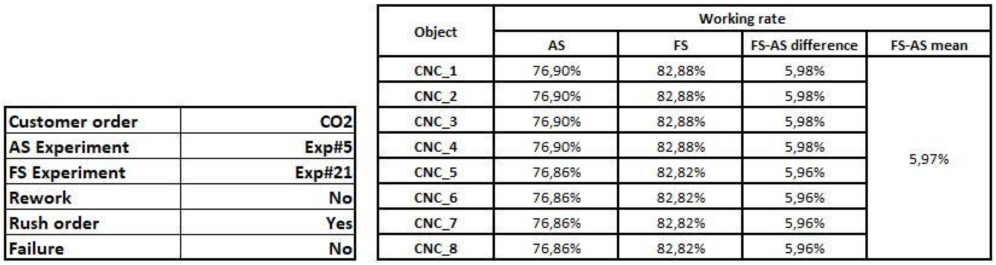


Customer order	CO1
AS Experiment	Exp#4
FS Experiment	Exp#20
Rework	Yes
Rush order	No
Failure	Yes

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	48,50%	52,47%	3,98%	4,26%
CNC_2	54,99%	59,50%	4,51%	
CNC_3	50,67%	54,81%	4,15%	
CNC_4	53,28%	57,64%	4,36%	
CNC_5	53,56%	57,96%	4,40%	
CNC_6	49,24%	53,28%	4,04%	
CNC_7	50,64%	54,79%	4,16%	
CNC_8	54,76%	59,24%	4,49%	

Figure 50 - CO1 Experiment#4-20 comparison

In relation to CO1 (Table 11) and Figure 50, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 4,26%.

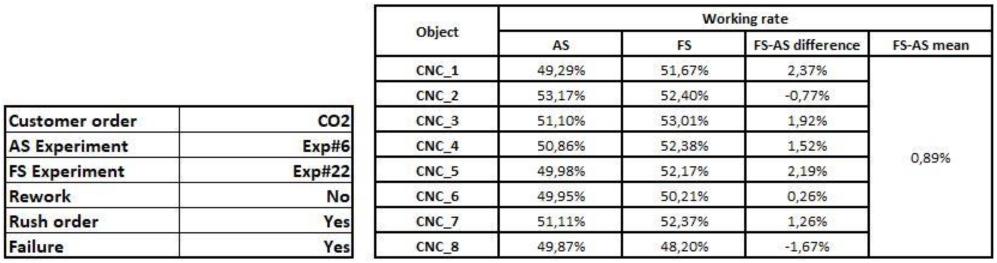


Customer order	CO2
AS Experiment	Exp#5
FS Experiment	Exp#21
Rework	No
Rush order	Yes
Failure	No

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	76,90%	82,88%	5,98%	5,97%
CNC_2	76,90%	82,88%	5,98%	
CNC_3	76,90%	82,88%	5,98%	
CNC_4	76,90%	82,88%	5,98%	
CNC_5	76,86%	82,82%	5,96%	
CNC_6	76,86%	82,82%	5,96%	
CNC_7	76,86%	82,82%	5,96%	
CNC_8	76,86%	82,82%	5,96%	

Figure 51 – CO2 Experiment#5-21 comparison

In relation to CO2 (Table 12) and Figure 51, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 5,97%.

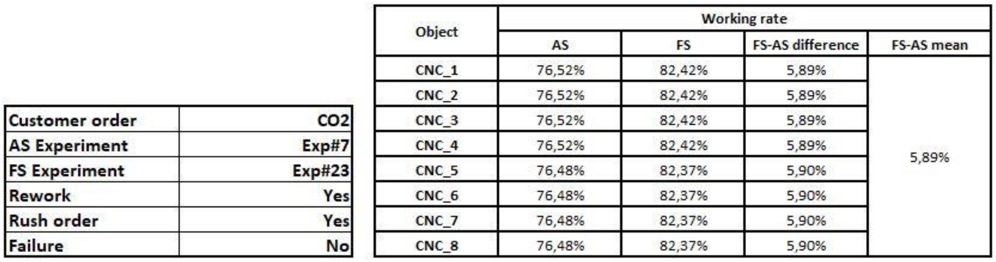


Customer order	CO2
AS Experiment	Exp#6
FS Experiment	Exp#22
Rework	No
Rush order	Yes
Failure	Yes

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	49,29%	51,67%	2,37%	0,89%
CNC_2	53,17%	52,40%	-0,77%	
CNC_3	51,10%	53,01%	1,92%	
CNC_4	50,86%	52,38%	1,52%	
CNC_5	49,98%	52,17%	2,19%	
CNC_6	49,95%	50,21%	0,26%	
CNC_7	51,11%	52,37%	1,26%	
CNC_8	49,87%	48,20%	-1,67%	

Figure 52 - CO2 Experiment#6-22 comparison

In relation to CO2 (Table 12) and Figure 52, the FS model's shows irregular values of performances related to all the CNC machines, even though, with a mean value of difference between FS and AS models of 0,89%, FS model has a slight advantage.

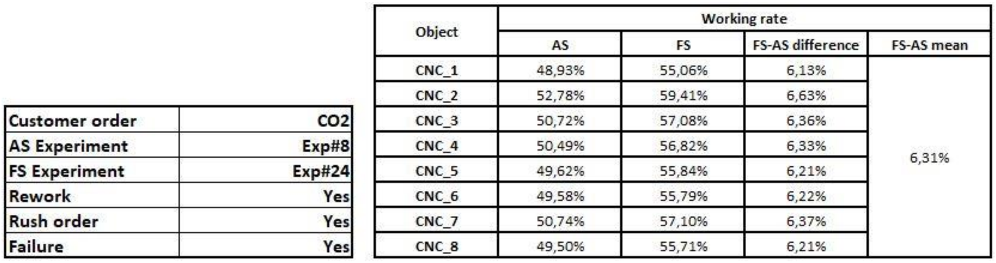


Customer order	**CO2**
AS Experiment	**Exp#7**
FS Experiment	**Exp#23**
Rework	**Yes**
Rush order	**Yes**
Failure	**No**

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	76,52%	82,42%	5,89%	5,89%
CNC_2	76,52%	82,42%	5,89%	
CNC_3	76,52%	82,42%	5,89%	
CNC_4	76,52%	82,42%	5,89%	
CNC_5	76,48%	82,37%	5,90%	
CNC_6	76,48%	82,37%	5,90%	
CNC_7	76,48%	82,37%	5,90%	
CNC_8	76,48%	82,37%	5,90%	

Figure 53 - CO2 Experiment#7-23 comparison

In relation to CO2 (Table 12) and Figure 53, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 5,89%.

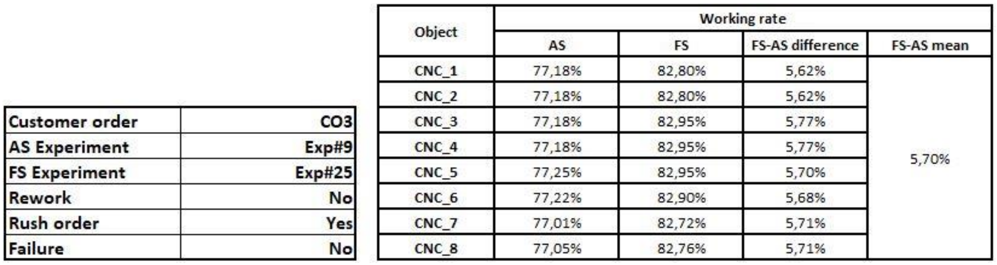


Customer order	**CO2**
AS Experiment	**Exp#8**
FS Experiment	**Exp#24**
Rework	**Yes**
Rush order	**Yes**
Failure	**Yes**

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	48,93%	55,06%	6,13%	6,31%
CNC_2	52,78%	59,41%	6,63%	
CNC_3	50,72%	57,08%	6,36%	
CNC_4	50,49%	56,82%	6,33%	
CNC_5	49,62%	55,84%	6,21%	
CNC_6	49,58%	55,79%	6,22%	
CNC_7	50,74%	57,10%	6,37%	
CNC_8	49,50%	55,71%	6,21%	

Figure 54 - CO2 Experiment#8-24 comparison

In relation to CO2 (Table 12) and Figure 54, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 6,31%.

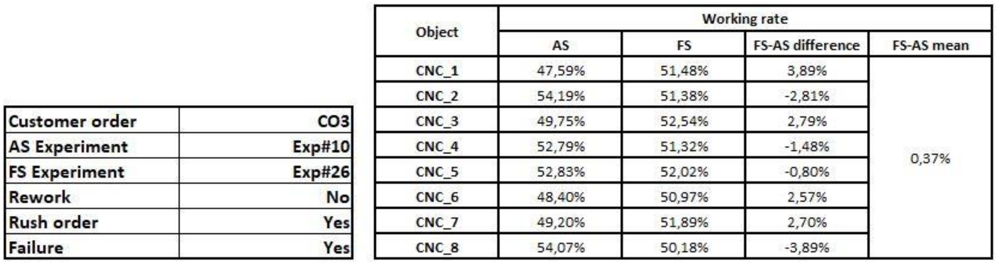


Customer order	**CO3**
AS Experiment	**Exp#9**
FS Experiment	**Exp#25**
Rework	**No**
Rush order	**Yes**
Failure	**No**

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	77,18%	82,80%	5,62%	5,70%
CNC_2	77,18%	82,80%	5,62%	
CNC_3	77,18%	82,95%	5,77%	
CNC_4	77,18%	82,95%	5,77%	
CNC_5	77,25%	82,95%	5,70%	
CNC_6	77,22%	82,90%	5,68%	
CNC_7	77,01%	82,72%	5,71%	
CNC_8	77,05%	82,76%	5,71%	

Figure 55 – CO3 Experiment#9-25 comparison

In relation to CO3 (Table 13) and Figure 55, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 5,70%.

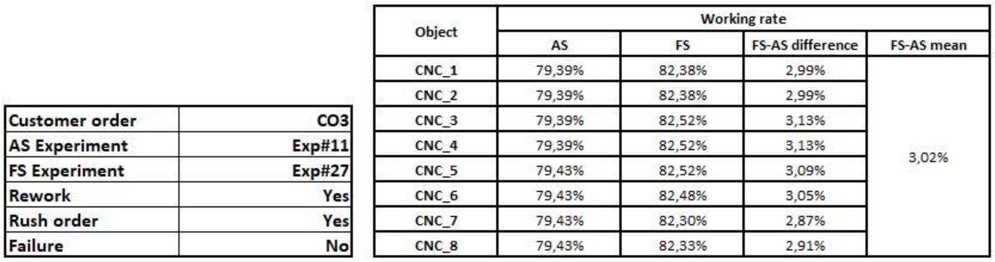


Customer order	**CO3**
AS Experiment	**Exp#10**
FS Experiment	**Exp#26**
Rework	**No**
Rush order	**Yes**
Failure	**Yes**

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	47,59%	51,48%	3,89%	0,37%
CNC_2	54,19%	51,38%	-2,81%	
CNC_3	49,75%	52,54%	2,79%	
CNC_4	52,79%	51,32%	-1,48%	
CNC_5	52,83%	52,02%	-0,80%	
CNC_6	48,40%	50,97%	2,57%	
CNC_7	49,20%	51,89%	2,70%	
CNC_8	54,07%	50,18%	-3,89%	

Figure 56 – CO3 Experiment#10-26 comparison

In relation to CO3 (Table 13) and Figure 56, the FS model's shows irregular values of performances related to all the CNC machines, even though, with a mean value of difference between FS and AS models of 0,89%, FS model has a slight advantage.

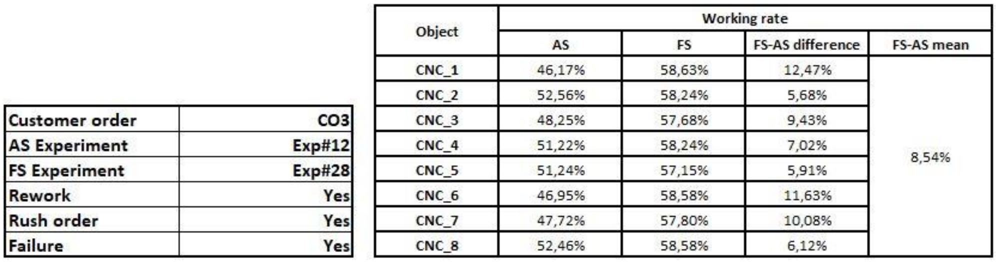


Customer order	**CO3**
AS Experiment	**Exp#11**
FS Experiment	**Exp#27**
Rework	**Yes**
Rush order	**Yes**
Failure	**No**

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	79,39%	82,38%	2,99%	3,02%
CNC_2	79,39%	82,38%	2,99%	
CNC_3	79,39%	82,52%	3,13%	
CNC_4	79,39%	82,52%	3,13%	
CNC_5	79,43%	82,52%	3,09%	
CNC_6	79,43%	82,48%	3,05%	
CNC_7	79,43%	82,30%	2,87%	
CNC_8	79,43%	82,33%	2,91%	

Figure 57 – CO3 Experiment#11-27 comparison

In relation to CO3 (Table 13) and Figure 57, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 3,02%.

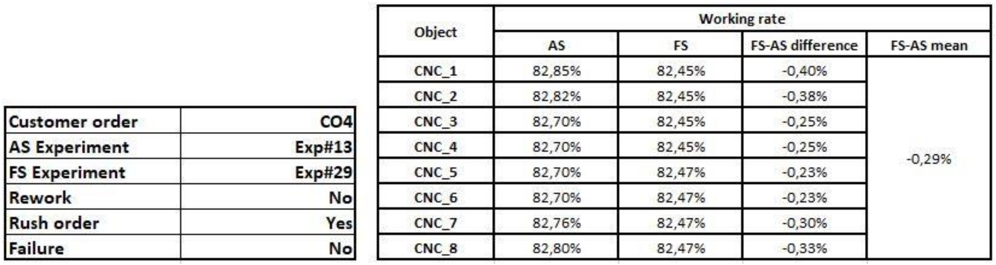


Customer order	CO3
AS Experiment	Exp#12
FS Experiment	Exp#28
Rework	Yes
Rush order	Yes
Failure	Yes

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	46,17%	58,63%	12,47%	8,54%
CNC_2	52,56%	58,24%	5,68%	
CNC_3	48,25%	57,68%	9,43%	
CNC_4	51,22%	58,24%	7,02%	
CNC_5	51,24%	57,15%	5,91%	
CNC_6	46,95%	58,58%	11,63%	
CNC_7	47,72%	57,80%	10,08%	
CNC_8	52,46%	58,58%	6,12%	

Figure 58 – CO3 Experiment#12-28 comparison

In relation to CO3 (Table 13) and Figure 58, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 8,54%.

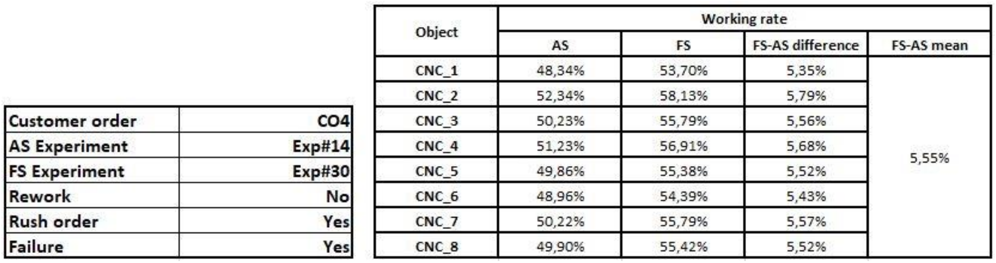


Customer order	CO4
AS Experiment	Exp#13
FS Experiment	Exp#29
Rework	No
Rush order	Yes
Failure	No

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	82,85%	82,45%	-0,40%	-0,29%
CNC_2	82,82%	82,45%	-0,38%	
CNC_3	82,70%	82,45%	-0,25%	
CNC_4	82,70%	82,45%	-0,25%	
CNC_5	82,70%	82,47%	-0,23%	
CNC_6	82,70%	82,47%	-0,23%	
CNC_7	82,76%	82,47%	-0,30%	
CNC_8	82,80%	82,47%	-0,33%	

Figure 59 – CO4 Experiment#13-29 comparison

In relation to CO4 (Table 14) and Figure 59, the FS model's shows irregular values of performances related to all the CNC machines, even though, with a mean value of difference between FS and AS models of -0,29%, AS model has a slight advantage.

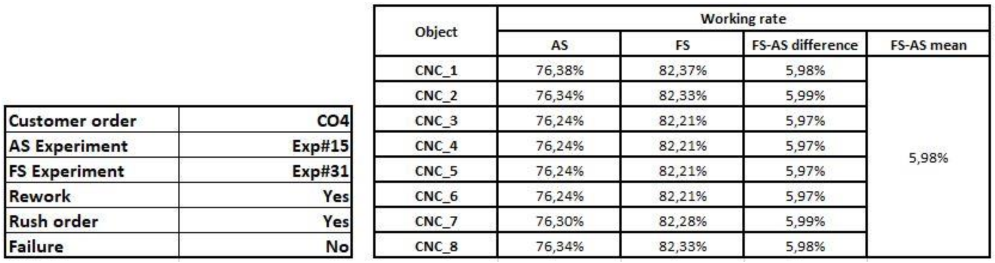


Customer order	CO4
AS Experiment	Exp#14
FS Experiment	Exp#30
Rework	No
Rush order	Yes
Failure	Yes

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	48,34%	53,70%	5,35%	5,55%
CNC_2	52,34%	58,13%	5,79%	
CNC_3	50,23%	55,79%	5,56%	
CNC_4	51,23%	56,91%	5,68%	
CNC_5	49,86%	55,38%	5,52%	
CNC_6	48,96%	54,39%	5,43%	
CNC_7	50,22%	55,79%	5,57%	
CNC_8	49,90%	55,42%	5,52%	

Figure 60 - CO4 Experiment#14-30 comparison

In relation to CO4 (Table 14) and Figure 60, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 5,55%.

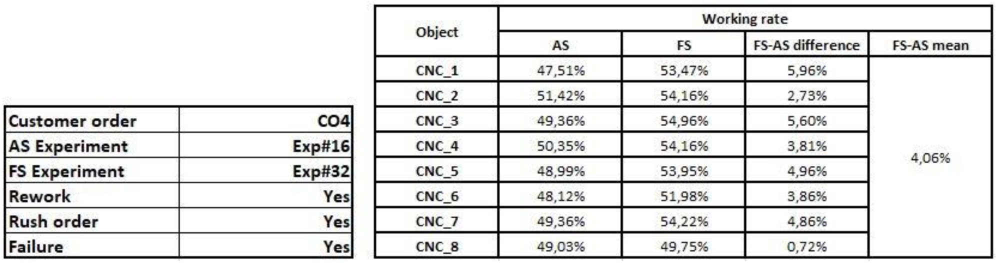


Customer order	CO4
AS Experiment	Exp#15
FS Experiment	Exp#31
Rework	Yes
Rush order	Yes
Failure	No

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	76,38%	82,37%	5,98%	5,98%
CNC_2	76,34%	82,33%	5,99%	
CNC_3	76,24%	82,21%	5,97%	
CNC_4	76,24%	82,21%	5,97%	
CNC_5	76,24%	82,21%	5,97%	
CNC_6	76,24%	82,21%	5,97%	
CNC_7	76,30%	82,28%	5,99%	
CNC_8	76,34%	82,33%	5,98%	

Figure 61 – CO4 Experiment#15-31 comparison

In relation to CO4 (Table 14) and Figure 61, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 5,98%.



Customer order	CO4
AS Experiment	Exp#16
FS Experiment	Exp#32
Rework	Yes
Rush order	Yes
Failure	Yes

Object	Working rate			
	AS	FS	FS-AS difference	FS-AS mean
CNC_1	47,51%	53,47%	5,96%	4,06%
CNC_2	51,42%	54,16%	2,73%	
CNC_3	49,36%	54,96%	5,60%	
CNC_4	50,35%	54,16%	3,81%	
CNC_5	48,99%	53,95%	4,96%	
CNC_6	48,12%	51,98%	3,86%	
CNC_7	49,36%	54,22%	4,86%	
CNC_8	49,03%	49,75%	0,72%	

Figure 62 – CO4 Experiment#16-32 comparison

In relation to CO4 (Table 14) and Figure 62, the FS model's has better performances related to all the CNC machines, with a mean value of difference between FS and AS models of 4,06%.

The analysis of the results reported in Figure 47, Figure 48, Figure 49 and Figure 50 and related to CO1 highlights that the parameter failure has a detrimental effect on resource utilization on both FS and AS. On the other side, rework parameter leads to a better resource utilization; rework and failure parameter evaluated together lead to the best result obtainable with CO1. Results reported in Figure 51, Figure 52, Figure 53 and Figure 54 and related to CO2 highlights the same behaviour of the previous experiment; the parameter failure has a detrimental effect on resource utilization on both FS and AS. Rework parameter leads to a better resource utilization while rework and failure parameter evaluated together lead to the best result obtainable with CO2. Same results while analysing the results from Figure 55, Figure 56, Figure 57 and Figure 58 and related to CO3; the failure parameter has a detrimental effect on resource utilization on both FS and AS. Rework parameter leads to a better resource utilization and rework and failure parameter evaluated together lead to the best result obtainable with CO3. CO4 in relation to the results of Figure 59, Figure 60, Figure 61 and Figure 62 shows a different behaviour if compared to the other types of customer orders; the best results of resource utilization is obtained with the rework parameter but the failure parameters is really close in comparison to it. The simulation with both the parameters lead to an overall good results of resource utilization but lesser than the result obtained individually. The final consideration about the resource utilization point out in the direction that the parameter rework has a positive influence while the failure, as it should, has a detrimental effect on the resources utilization. Nevertheless, FS model has a slight advantage also in this specific case. The results of the combined parameters utilization lead to overall better results.

5.4- Conclusions

The present research study investigates the possibility of LM implementation in a HVLV environment. Most of the companies that shares this specific manufacturing environment are SMEs (Jina, Bhattacharya and Walton, 1997). Case research is used in order to obtain evidences of a potential application of LM tools that are suitable for HVLV environment through the adoption of a simulation software. Specifically, single case approach has been carefully evaluated and identified as the best method in order to obtain detailed analysis and gathering useful data necessary to reach valuable insight on this topic (Crotty, 1998; Voss, Tsikriktsis and Frohlich, 2002). The objective of the research is helping HVLV companies to understand the feasibility of implementing LM tools, and identify which one, in order to extend the LM operational benefits. The three research questions that drove the study work highlighted the main point needed in order to reach a correct solution; the first question is related about the applicability of LM tools to HVLV environment while the second one question which of this tools can be applied and how. If some of LM tools can be applied, a deep analysis on the main benefit and advantage that can be obtained is critical. The literature review highlights that some LM tools can be utilized in HVLV environment as stated by (Bokhorst and Slomp, 2010) and (Portioli-Staudacher and Tantardini, 2008) even though Portioli admit that not every LM tools implementation can be successful or even possible. In the field of HVLV LM compatible tools, CONWIP is one of the most studied, and cited, pull system method that has shown interesting performance in replacement of the well-known kanban (Spearman, Woodruff and Hopp, 1990). For this reason, and thanks to the easiness of a probable implementation in a real industrial case, CONWIP has been chosen as a pull system for the future state of a company named Alpha, an Italian HVLV SME. The results obtained shows good overall performance when compared to the actual state of the company, that has no pull system. The makespan differences between FS and AS shows a generalized good performance except for the CO3, whose behavior deserves further investigation. Four type of customer demands has been analyzed in relation to three main parameters: failure, rework and rush orders. The behavior analyzed point out in the direction that failures have a detrimental effect on the resource utilization while rework shows a good response. The combined effect even shows good results. Although gathered data shows different values and depending on the single case, it can be asserted that LM implementation in HVLV environment can be successful and the companies that has similar manufacturing environment can benefit from this application. Even though other works has developed a simulation model for a HVLV research (Bokhorst and Slomp, 2010), the only other research work with in-field insights has been done by (Romagnoli, 2015) and the results obtained confirm the validity of this research field. The main novel contribution of this research is related to the application of a simulation model for HVLV companies in the high-fashion industry while the main limitation is the generalizability due to the single case study. In this regard, the next possible step could be the application of this HVLV framework to other companies sharing the same manufacturing environment in order to gain insights in similar types of companies and obtained a more generalized application of the simulation model.

References1

In the next pages the references mentioned within this PhD research are listed.

Achanga, P. *et al.* (2006) 'Critical success factors for lean implementation within SMEs', *Journal of Manufacturing Technology Management*, 17(4), pp. 460–471. Available at: https://doi.org/10.1108%2F17410380610662889.

Adrodegari, F. *et al.* (2015) 'Engineer-to-order (ETO) production planning and control: An empirical framework for machinery-building companies', *Production Planning and Control*, 26(11), pp. 910–932. doi: 10.1080/09537287.2014.1001808.

Ahmad, M. M. and Dhafr, N. (2002) 'Establishing and improving manufacturing performance measures', *Robotics and Computer-Integrated Manufacturing*, 18(3–4), pp. 171–176. doi: 10.1016/S0736-5845(02)00007-8.

Alagumurthi, N., Palaniradja, K. and Soundararajan, V. (2006) 'Optimization of Grinding Process Through Design of Experiment (DOE)—A Comparative Study Optimization of Grinding Process Through Design of Experiment (DOE)—A Comparative Study', *Materials and Manufacturing Processes*, 21(October 2013), pp. 19–21. doi: 10.1081/AMP-200060605.

Amaro, Graça; Hendry, Linda; Kingsman, B. (1999) 'Competitive advantage, customisation and a new taxonomy for non make-to-stok companies', *International Journal of Operations & Production Management*, 19(4), pp. 349–371.

Ansari, A. and Modarress, B. (1988) 'JIT purchasing as a quality and productivity centre', *International Journal of Production Research*, 26(1), pp. 19–26. Available at: https://doi.org/10.1080%2F00207548808947838.

Belekoukias, I., Garza-Reyes, J. A. and Kumar, V. (2014) 'The impact of lean methods and tools on the operational performance of manufacturing organisations', *International Journal of Production Research*, 52(18), pp. 5346–5366. doi: 10.1080/00207543.2014.903348.

Bezerra, L. N. M. and da Silva, M. T. (2015) 'Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth', *IFIP Advances in Information and Communication Technology*, 459(August), pp. 500–506. doi: 10.1007/978-3-319-22756-6.

Bhamu, J. and Sangwan, K. S. (2014) 'Lean manufacturing: Literature review and research issues', *International Journal of Operations and Production Management*, 34(7), pp. 876–940. doi: 10.1108/IJOPM-08-2012-0315.

Bhandwale, A. and Kesavadas, T. (2008) 'A methodology to incorporate product mix variations in cellular manufacturing', *Journal of Intelligent Manufacturing*, 19(1), pp. 71–85. doi: 10.1007/s10845-007-0046-4.

Bhasin, S. and Burcher, P. (2006) 'Lean viewed as a philosophy', *Journal of Manufacturing Technology Management*, 17(1), pp. 56–72. Available at: https://doi.org/10.1108%2F17410380610639506.

Bokhorst, J. A. C. and Slomp, J. (2008) 'Towards Takt Time Controlled Production Units in Low Volume High Variety Environments', in *15th International Annual Conference of the European Operations Management Association*, pp. 1–10.

Bokhorst, J. A. C. and Slomp, J. (2010) 'Lean production control at a high-variety, low-volume parts manufacturer', *Interfaces*, 40(4), pp. 303–312. doi: 10.1287/inte.1100.0503.

Bortolotti, T., Boscari, S. and Danese, P. (2015) 'Successful lean implementation: Organizational culture and soft lean practices', *International Journal of Production Economics*. Elsevier, 160, pp. 182–201. doi: 10.1016/j.ijpe.2014.10.013.

Bouma, G. D. and Ling, R. (2004) *The research process*. Oxford University Press, USA.

Boyle, T. A. and Scherrer-Rathje, M. (2009) 'An empirical examination of the best practices to ensure manufacturing flexibility', *Journal of Manufacturing Technology Management*, 20(3), pp. 348–366. Available at: https://doi.org/10.1108%2F17410380910936792.

Buetfering, B. *et al.* (2016) 'Lean in high variety, low volume production environments – A Literature Review and Maturity Model', *Conference: EurOMA 2016*, (June), p. 11. Available at: https://www.researchgate.net/profile/Benjamin_Buetfering/publication/304569890_Lean_in_high_variety_low_volume_production_environments_-_A_Literature_Review_and_Maturity_Model/links/5773890708ae1b18a7dcc55d.pdf.

Condra, L. (2001) *Reliability improvement with design of experiment*. CRC Press.

Corbett, L. M. (1998) 'Benchmarking manufacturing performance in Australia and New Zealand', 5(4), pp. 271–282.

Cortes, H. *et al.* (2016) 'Strategic Lean Management: Integration of operational Performance Indicators for strategic Lean management', *IFAC-PapersOnLine*. Elsevier B.V., 49(12), pp. 65–70. doi: 10.1016/j.ifacol.2016.07.551.

Cransberg, V. *et al.* (2016) 'Handling the complexities of real-life job shops when implementing workload control: A decision framework and case study', *International Journal of Production Research*, 54(4), pp. 1094–1109. doi: 10.1080/00207543.2015.1047974.

Crotty, M. (1998) *Introduction: the research process*, *The foundations of social research: Meaning and perspective in the research process*. doi: 10.1017/CBO9781107415324.004.

Dangayach, G. S. and Deshmukh, S. G. (2001) 'Manufacturing strategy', *International Journal of Operations & Production Management*, 21(7), pp. 884–932. Available at: https://doi.org/10.1108%2F01443570110393414.

Davies, A. J. and Kochhar, A. K. (2002) 'Manufacturing best practice and performance studies: a critique', *International Journal of Operations & Production Management*, 22(3), pp. 289–305. Available at: https://doi.org/10.1108%2F01443570210417597.

Detty, R. B. and Yingling, J. C. (2000) 'Quantifying benefits of conversion to lean manufacturing with discrete event simulation: A case study', *International Journal of Production Research*, 38(2), pp. 429–445. Available at: https://doi.org/10.1080%2F002075400189509.

Eisenhardt, K. M. and Graebner, M. E. (2007) 'Theory building from cases: Opportunities and challenges', *Academy of Management Journal*. doi: 10.5465/AMJ.2007.24160888.

European Commision (2015) *User guide to the SME Definition*, *User guide to the SME Definition*. doi: 10.2873/782201.

European Union (2003) 'Commission Recommendation of 6 May 2003 concerning the definition of micro, small and medium-sized enterprises', *Official Journal of the European Union*, pp. 36–41. doi: 10.1017/CBO9781107415324.004.

Flynn, B. (1990) 'Empirical research methods in operations management', *Journal of Operations Management*, 9(2), pp. 250–284. doi: 10.1016/0272-6963(90)90098-X.

Gaury, E. G. A., Pierreval, H. and Kleijnen, J. P. C. (2000) 'Evolutionary approach to select a pull system among Kanban, Conwip and Hybrid', *Journal of Intelligent Manufacturing*, 11(2), pp. 157–167. doi: 10.1023/A:1008938816257.

Geraghty, J. and Heavey, C. (2004) 'A comparison of hybrid push/pull and CONWIP/pull production inventory control policies', *International Journal of Production Economics*, 91(1), pp. 75–90. doi: 10.1016/S0925-5273(03)00210-X.

Germs, R. and Riezebos, J. (2010) 'Workload balancing capability of pull systems in MTO production', *International Journal of Production Research*, 48(8), pp. 2345–2360. doi: 10.1080/00207540902814314.

Giornale delle Pmi (2017) *Confindustria: il manifatturiero traina la ripresa. L'Italia mantiene il settimo* *posto tra i paesi più industrializzati, il secondo in Europa*. Available at: https://www.giornaledellepmi.it/confindustria-il-manifatturiero-traina-la-ripresa-litalia-mantiene-il-settimo-posto-tra-i-paesi-piu-industrializzati-il-secondo-in-europa/.

Gosling, J. . *et al.* (2007) 'Defining the lean and agile characteristics of engineer-to-order construction projects', *CME 2007 Conference - Construction Management and Economics: 'Past, Present and Future'*, 1(July), pp. 773–785. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84877592573&partnerID=40&md5=526172bddf7a94f969a5728473db7f03.

Gosling, J. and Naim, M. M. (2009) 'Engineer-to-order supply chain management: A literature review and research agenda', *International Journal of Production Economics*. Elsevier, 122(2), pp. 741–754. doi: 10.1016/j.ijpe.2009.07.002.

Hallgren, M. and Olhager, J. (2009) 'Lean and agile manufacturing: External and internal drivers and performance outcomes', *International Journal of Operations and Production Management*, 29(10), pp. 976–999. doi: 10.1108/01443570910993456.

Harrod, S. and Kanet, J. J. (2013) 'Applying work flow control in make-to-order job shops', *International Journal of Production Economics*. Elsevier, 143(2), pp. 620–626. doi: 10.1016/j.ijpe.2012.02.017.

Hendry, L., Huang, Y. and Stevenson, M. (2013) 'Workload control: Successful implementation taking a contingency-based view of production planning and control', *International Journal of Operations and Production Management*. doi: 10.1108/01443571311288057.

Hines, P., Holwe, M. and Rich, N. (2004) 'Learning to evolve: A review of contemporary lean thinking', *International Journal of Operations and Production Management*, 24(10), pp. 994–1011. doi: 10.1108/01443570410558049.

Hopp, W. J. and Spearman, M. L. (2004) 'To Pull or Not to Pull: What Is the Question?', *Manufacturing & Service Operations Management*, 6(2), pp. 133–148. doi: 10.1287/msom.1030.0028.

Huang, H. and Irani, S. (2003) 'An enhanced systematic layout planning process for high-variety low-volume (HVLV) manufacturing facilities', in *The 17th International Conference on Production Research*.

Jaegler, Y. *et al.* (2017) 'The ConWip production control system: a systematic review and classification', *International Journal of Production Research*. Taylor & Francis, 7543(September), pp. 1–22. doi: 10.1080/00207543.2017.1380325.

Jina, J., Bhattacharya, A. K. and Walton, A. D. (1997) 'Applying lean principles for high product variety and low volumes: some issues and propositions', *Logistics Information Management*. MCB UP Ltd, 10(1), pp. 5–13. doi: 10.1108/09576059710159655.

Junior, M. L. and Filho, M. G. (2010) 'Variations of the kanban system: Literature review and classification', *International Journal of Production Economics*, 125(1), pp. 13–21. Available at: https://doi.org/10.1016%2Fj.ijpe.2010.01.009.

Kackar, R. N. (1989) 'Off-Line Quality Control, Parameter Design, and the Taguchi Method', in *Quality Control, Robust Design, and the Taguchi Method*. Springer, pp. 51–76.

Katic, M. and Agarwal, R. (2018) 'The Flexibility Paradox: Achieving Ambidexterity in High-Variety, Low-Volume Manufacturing', *Global Journal of Flexible Systems Management*. Springer India, 19(s1), pp. 69–86. doi: 10.1007/s40171-018-0184-x.

Khojasteh, Y. and Sato, R. (2015) 'Selection of a pull production control system in multi-stage production processes', *International Journal of Production Research*, 53(14), pp. 4363–4379. doi: 10.1080/00207543.2014.1001530.

Land, M. J. and Gaalman, G. J. C. (2009) 'Production planning and control in SMEs: time for change', *Production Planning & Control*, 20(7), pp. 548–558. doi: 10.1080/09537280903034230.

Law, A. M. and Kelton, D. W. (2000) 'Simulation modeling and analysis'. McGraw-Hill.

Lean Enterprise Institute (2008) *Lean Lexicon: a graphical glossary for Lean Thinkers*. Lean Enterprise Institute. Available at: https://www.lean.org/Bookstore/ProductDetails.cfm?SelectedProductId=380 (Accessed: 28 October 2017).

Lean Enterprise Institute (2010) *Value-Stream Mapping*, *Lean Enterprise Institute*. Available at: https://www.lean.org/lexicon/value-stream-mapping (Accessed: 28 October 2017).

Lean Enterprise Institute (2011a) *5S*, *Lean Enterprise Institute*. Available at: https://www.lean.org/lexicon/five-ss (Accessed: 28 October 2017).

Lean Enterprise Institute (2011b) *Kanban*, *Lean Enterprise Institute*. Available at: https://www.lean.org/lexicon/kanban (Accessed: 28 October 2017).

Lean Enterprise Institute (2012a) *Pull Production*, *Lean Enterprise Institute*. Available at: https://www.lean.org/lexicon/pull-production (Accessed: 28 October 2017).

Lean Enterprise Institute (2012b) *Standardized Work Chart*, *Lean Enterprise Institute*. Available at: https://www.lean.org/lexicon/standardized-work (Accessed: 28 October 2017).

Lean Enterprise Institute (2012c) *Standardized Work Job Instruction Sheet*, *Lean Enterprise Institute*. Available at: https://www.lean.org/common/display/?o=2189 (Accessed: 28 October 2017).

Lewis, M. W. (1998) 'Iterative triangulation: a theory development process using existing case studies', *Journal of Operations Management*. doi: 10.1016/S0272-6963(98)00024-2.

Marek, R. P. *et al.* (2007) 'Defining the lean and agile characteristics of engineer-to-order construction projects', *Procedia CIRP*. Elsevier B.V., 104(July), pp. 773–785. doi: 10.1016/S0305-0483(00)00033-5.

Marodin, G. A. *et al.* (2015) 'How context factors influence lean production practices in manufacturing cells', *The International Journal of Advanced Manufacturing Technology*, 79(5–8), pp. 1389–1399. doi: 10.1007/s00170-015-6944-2.

McIntosh, R. I. *et al.* (2000) 'A critical evaluation of Shingos SMED (Single Minute Exchange of Die) methodology', *International Journal of Production Research*, 38(11), pp. 2377–2395. Available at: https://doi.org/10.1080%2F00207540050031823.

Nasri, I., Boukezzoula, R. and Habchi, G. (2012) *A mathematical model for HVLV systems scheduling and optimization with periodic preventive maintenance using (Max, +) Algebra*, *IFAC Proceedings Volumes (IFAC-PapersOnline)*. IFAC. doi: 10.3182/20120523-3-RO-2023.00125.

Ohno, T. (1988) *Toyota Production System: Beyond Large-Scale Production*, *Productivity Press*. doi: 10.1108/eb054703.

Ohno, T. (1998) *Toyota Production System: Beyond Large Scale Production*. Productivity Press, Portland.

Ovalle, O. R. and Marquez, A. C. (2003) 'Exploring the utilization of a CONWIP system for supply chain management. A comparison with fully integrated supply chains', *International Journal of Production Economics*, 83(2), pp. 195–215. doi: 10.1016/S0925-5273(02)00328-6.

Özbayrak, M., Papadopoulou, T. C. and Samaras, E. (2006) 'A flexible and adaptable planning and control system for an MTO supply chain system', *Robotics and Computer-Integrated Manufacturing*, 22(5–6), pp. 557–565. doi: 10.1016/j.rcim.2005.12.011.

Petroni, A., Zammori, F. and Marolla, G. (2017) 'World class manufacturing in make-to-order batch-production SMEs: An exploratory analysis in northern Italy', *International Journal of Business Excellence*, 11(2), pp. 241–275. doi: 10.1504/IJBEX.2017.081434.

Pettersen, J. A. and Segerstedt, A. (2009) 'Restricted work-in-process: A study of differences between Kanban and CONWIP', *International Journal of Production Economics*, 118(1), pp. 199–207. doi:

10.1016/j.ijpe.2008.08.043.

Portioli-Staudacher, A. and Tantardini, M. (2008) 'Lean Production implementation: a comparison between repetitive and non-repetitive companies', in *Preprints of 15th International Working seminar on Production Economics*, pp. 405–416.

Prajogo, D. and Olhager, J. (2012) 'Supply chain integration and performance: The effects of long-term relationships, information technology and sharing, and logistics integration', *International Journal of Production Economics*. Elsevier, 135(1), pp. 514–522. doi: 10.1016/j.ijpe.2011.09.001.

Robert Yin, T. O. (2011) 'Case study research: design and methods', (2008), pp. 2008–2011.

Romagnoli, G. (2015) 'Design and simulation of CONWIP in the complex flexible job shop of a Make-To-Order manufacturing firm', *International Journal of Industrial Engineering Computations*, 6(1), pp. 117–134. doi: 10.5267/j.ijiec.2014.8.003.

Rosing, M. von, Scheel, H. von and Scheer, A.-W. (2014) *The Complete Business Process Handbook: Body of Knowledge from Process Modeling to BPM, Volume 1*. Edited by Lean Enterprise Institute. Lean Enterprise Institute. Available at: https://books.google.com/books?id=RT7LAwAAQBAJ&pgis=1 (Accessed: 28 October 2017).

Rother, M. and Shook, J. (2009) *Learning to See: Value Stream Mapping to Add Value and Eliminate MUDA*. Edited by Productivity Press. The Lean Enterprise Institute.

Rowlands, H., Antony, J. and Knowles, G. (2000) 'An application of experimental design for process optimisation', *The TQM Magazine*, 12(2), pp. 78–84. doi: 10.1108/09544780010318325.

Shah, R. and Ward, P. T. (2003) 'Lean manufacturing: Context, practice bundles, and performance', *Journal of Operations Management*, 21(2), pp. 129–149. doi: 10.1016/S0272-6963(02)00108-0.

Shah, R. and Ward, P. T. (2007) 'Defining and developing measures of lean production', *Journal of Operations Management*, 25(4), pp. 785–805. doi: 10.1016/j.jom.2007.01.019.

Slomp, J., Bokhorst, J. a. C. and Germs, R. (2009) 'A lean production control system for high-variety/low-volume environments: a case study implementation', *Production Planning & Control*, 20(7), pp. 586–595. doi: 10.1080/09537280903086164.

Sohal, A. S. and Egglestone, A. (1994) 'Lean Production: Experience among Australian Organizations', *International Journal of Operations & Production Management*, 14(11), pp. 35–51. doi: 10.1108/01443579410068639.

Spearman, M. L., Woodruff, D. L. and Hopp, W. J. (1990) 'CONWIP: A pull alternative to kanban', *International Journal of Production Research*, 28(5), pp. 879–894. doi: 10.1080/00207549008942761.

Spearman, M. L. and Zazanis, M. a. (1992) 'Push and Pull Production Systems: Issues and Comparisons', *Operations Research*, 40(July 2015), pp. 521–532. doi: 10.1287/opre.40.3.521.

Staudacher, A. P. and Tantardini, M. (2012) 'Lean implementation in non-repetitive companies: a survey and analysis', *International Journal of Services and Operations Management*, 11(4), p. 385. doi: 10.1504/IJSOM.2012.046076.

Stevenson, M., Hendry, L. C. and Kingsman, B. G. (2005) 'A review of production planning and control: The applicability of key concepts to the make-to-order industry', *International Journal of Production Research*, 43(5), pp. 869–898. doi: 10.1080/0020754042000298520.

Sugimori, Y. *et al.* (1977) 'Toyota Production System and Kanban System Materialization of Just In Time and Respect For Human System', *International Journal of Production Research*, pp. 553–564. doi: 10.1080/00207547708943149.

Supsomboon, S. and Vajasuvimon, A. (2016) 'Simulation model for job shop production process improvement in machine parts manufacturing', *International Journal of Simulation Modelling*, 15(4), pp. 611–622. doi: 10.2507/IJSIMM15(4)3.352.

Tamani, K., Boukezzoula, R. and Habchi, G. (2011) 'Application of a continuous supervisory fuzzy control on a discrete scheduling of manufacturing systems', *Engineering Applications of Artificial Intelligence*. Elsevier, 24(7), pp. 1162–1173.

Tardif, V. and Maaseidvaag, L. (2001) 'An adaptive approach to controlling kanban systems', *European Journal of Operational Research*, 132(2), pp. 411–424. doi: 10.1016/S0377-2217(00)00119-3.

Thomassen, M. K. and Alfnes, E. (2017) *Managing Complexity*, *Proceedings of the 8th World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2015), Montreal, Canada, October 20th-22th, 2015*. Edited by J. Bellemare et al. doi: 10.1007/978-3-319-29058-4.

Thürer, M. *et al.* (2012) 'Workload control and order release: A lean solution for make-to-order companies', *Production and Operations Management*, 21(5), pp. 939–953. doi: 10.1111/j.1937-5956.2011.01307.x.

Thürer, M. *et al.* (2017) 'On the backlog-sequencing decision for extending the applicability of ConWIP to high-variety contexts: an assessment by simulation', *International Journal of Production*

Research. Taylor & Francis, 55(16), pp. 4695–4711. doi: 10.1080/00207543.2017.1281462.

Tsoukas, H. (2009) 'Craving for generality and small-N studies: A Wittgensteinian approach towards the epistemology of the particular in organization and management studies', *The Sage handbook of organizational research methods*. Sage London, pp. 285–301.

Tyagi, S. *et al.* (2015) 'Lean tools and methods to support efficient knowledge creation', *International Journal of Information Management*. Elsevier Ltd, 35(2), pp. 204–214. doi: 10.1016/j.ijinfomgt.2014.12.007.

Veldman, J. and Klingenberg, W. (2009) 'Applicability of the capability maturity model for engineer-to-order firms', *International Journal of Technology Management*, 48(2), p. 219. doi: 10.1504/IJTM.2009.024917.

Vinodh, S. and Joy, D. (2012) 'Structural Equation Modelling of lean manufacturing practices', *International Journal of Production Research*, 50(6), pp. 1598–1607. doi: 10.1080/00207543.2011.560203.

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002) 'Case research in operations management', *International Journal of Operations and Production Management*, 22(2), pp. 195–219. doi: 10.1108/01443570210414329.

White, R. E. and Prybutok, V. (2001) 'The relationship between JIT practices and type of production system', *Omega*, 29(2), pp. 113–124. doi: 10.1016/S0305-0483(00)00033-5.

Wikner, J. and Rudberg, M. (2005) 'Integrating production and engineering perspectives on the customer order decoupling point', *International Journal of Operations and Production Management*, 25(7), pp. 623–641. doi: 10.1108/01443570510605072.

Womack, J. P. and Jones, D. T. (1996) *Lean Thinking*, *The Library Quarterly*. doi: 10.1086/601582.

Womack, J. P., Jones, D. T. and Roos, D. (1990) *The Machine that Changed the World: The Story of Lean Production*, *World*. doi: 10.1016/0024-6301(92)90400-V.

Yang, T., Fu, H. P. and Yang, K. Y. (2007) 'An evolutionary-simulation approach for the optimization of multi-constant work-in-process strategy-A case study', *International Journal of Production Economics*, 107(1), pp. 104–114. doi: 10.1016/j.ijpe.2006.02.014.

Yin, R. K. (2009) *Case Study Research: Design and Methods*, *Essential guide to qualitative methods in organizational research*. doi: 10.1097/FCH.0b013e31822dda9e.

Yin, Y., Stecke, K. E. and Li, D. (2018) 'The evolution of production systems from Industry 2.0 through Industry 4.0', *International Journal of Production Research*. Taylor & Francis, 56(1–2), pp. 848–

861. doi: 10.1080/00207543.2017.1403664.