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Lean production planning and control in semi-process industries

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Preface

"Lean production planning and control in semi-process industries" is the work developed as a master's thesis in production and quality engineering. It has been done in the NTNU from September 2014 until February 2015 as part of the ERASMUS + exchange program.

This project was proposed by the supervisor Erlend Alfnes who gave me all the tools and resources necessaries to get into it.

This is written to be understood for any industrial management engineer with notions of manufacturing industries.

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Abstract

Process Industries have traditionally been lumped together on the basis of producing non-discrete products. However, some of these industries are hybrid of process sector as at some point of their production process the products are discretized and treated as discrete units. This hybrid manufacturing environments can be classified as another type of manufacturing industries, under the name of semi-process industries. The notion of the discretization point which reflects this hybridity was firstly introduced by Abdulmalek, Rajgopal, and Needy (2006) and later highlighted by Pool, Wijngaard, and Van der Zee (2011).

Production planning and control environments are defined by the interaction of the customer demand, production process and product produced. Although they are not totally dependent one from each other, these three elements are closely related. This dependency was already reflected in the traditional product-process matrix from Hayes and Wheelwright (1984), but the matrix captured an overall dependency without analysing in a more granular way. This matrix has been expanded and gained detail with the research of current classification for production planning and control and process manufacturing environments. With this information, manufacturing environments for semi-process industries have been studied and characterised.

Lately, manufacturing environments have been focusing their efforts on reaching levels of optimisation. Moreover, reducing waste on every one of their production steps and making their processes more flexible in order to accommodate wider demand variation and order fulfilment. Therefore, lean manufacturing methodologies have been implemented in manufacturing industries in order to reach these goals. Production planning and control tools (PPC tools) are between all these lean concepts a small portion which can have reliable profits. Applicability in discrete sectors has been widely demonstrated (Bokhorst & Slomp, 2010; Liker, 2004). On the other hand, applicability of lean methodologies on process sectors still remains behind due to the rigid properties of these sectors (i.e. inflexible equipment, long set-up and changeover times). Therefore, applying this manufacturing concepts and tools in semi-process environments can have an easier implementation. Scholars as Abdulmalek et al. (2006), Lyons, Vidamour, Jain, and Sutherland (2013) among others, have been studying and applying these concepts so far.

At this thesis, five traditional lean PPC tools are identified and studied to be applied in semi-process industries this being reflected at the product-process matrix. The tools analysed are Kanban pull production, Heijunka, Cyclic wheel planning, Takt time and Cellular manufacturing. From all these tools, cyclic planning methodologies (which include Heijunka and cyclic wheels between others) have been found the most effective lean PPC tool due to the high capacity of adaptation to different process and product profiles. To apply these tools, not only the process characteristics but also the product demand segmentation in terms of runners/repeaters/strangers is important. That is because each product portfolio requires a different planning and replenishment approach.

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I would also like to thanks all the help and attention received from Dr. Phillip Spenhoff. Without that I would still be lost trying to deal with all the work that a thesis like this carries.

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J.F

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Abbreviations

APICS	American Production and Inventory Control Society
ATO	Assemble to order
BOM	Bill of material
BTO	Blend to order
CODP	Customer order decoupling point
CONWIP	Constant work in process
DI	Discrete industries
DP	Discretization point
ETO	Engineer to order
EOQ	Economic order quantity
FTO	Finish to order
JIT	Just in time
MTO	Make to order
MTS	Make to stock
PI	Process industries
PPC	Production planning and control
PTO	Package to order
ROP	Re-order point
SCM	Supply Chain Management
SKU	Stock keeping unit
SMED	Single minute exchange of die
SPI	Semi-process industries
TPM	Total productive maintenance
TPS	Toyota production system
VAOE	Value added at order entry
VS	Visual systems
VSM	Value stream mapping
WIP	Work in process
WS	Work standardization

Chapter 1 - Introduction

1.1 Introduction

Lean manufacturing has emerged as a solution to reduce waste in production processes implementing the concepts originated at the Toyota Production System (TPS) developed by Eiji Toyoda, Taiichi Ohno and Shigeo Shingo at the beginnings of the 1940s. The applicability to discrete industries, i.e. assembly industries, has been straightforward. However, applicability in process industries, i.e. continuous industries, still remains behind. Recently scholars as for example Abdulmalek et al. (2006), King (2009), Lyons et al. (2013), Mahapatra and Mohanty (2007), Melton (2005) and Pool et al. (2011) have been studying and implementing some of these lean concepts at process industries reaching remarkable results. Semi-process industries are somewhere between process and discrete industries due to their process and product hybridity. The discretization point (DP) is known as the point where object type changes from continuous to discrete (Abdulmalek et al., 2006, p. 21). In this case, the fact of being a mixed process, semi-process industries benefits from the previous experiences and favourable results on discrete industries, but still lacking understanding of the scope and impact on the non-discrete part.

Lean manufacturing aim to reduce waste in every stage of the production process. It is based on five principles:

- Identifying value from the perspective of the customer
- Value stream mapping in order to detect value-added and non-value added activities
- Make production flow by eliminating non-value-added activities
- Pull production from customer demand
- Continuously eliminate all waste in order to reach process perfection.

Lean production planning and control (PPC) tools are these tools dealing with the alignment of production and demand (Lyons et al., 2013). Applicability of these tools can help industries to smooth the production process, reaching high service levels and reducing production and lead times. Scholars as King (2009), Powell, Alfnes, and Semini (2010) and Pool et al. (2011) have lately applied these concepts at process and semi-process environments. At this thesis the following lean PPC tools are analysed and proposed to be applied at these semi-process environments:

- Cellular Manufacturing is a lean PPC tool capable to reach high levels of production flexibility and reduce production times by producing products in families.
- Takt time is a lean PPC tool which establishes a common production rhythm or “takt” to reduce spare times.
- Kanban is a signalling replenishment methodology to produce under actual customer demand, this reducing work in progress (WIP).
- Cyclic planning is a repeated methodology of planning that aims to mitigate the volume variation in demand with optimized sequences of production runs. Beneath cyclic planning methodologies two main distinctions are made. Heijunka or levelled production, which is a scheduling concept to balance production volume and product

mix. And cyclic wheels, which are an evolution of Heijunka planning methodology where a repeated sequence of products is produced in a cyclic way.

Other lean tools can be used at manufacturing processes to facilitate production planning and control systems applicability. The tools proposed at this thesis are:

- Total productive maintenance (TPM), which aims to reach high service levels of equipment by maintenance methodologies.
- Single minute exchange of dies (SMED) is a methodology to reduce changeover times.

1.2 Problem description

Semi-process industries have been significantly understudied and characterised than discrete industries. Scholars have identified the hybridity inherent in some processes as a differential element, but there are no specific characterisations or models for these semi-process environments.

Lean production planning and control (PPC) tools application in process industries has been recently introduced by different scholars such as King(2009) and Pool et al(2011) in order to reduce waste and smooth the production process. However, application of these tools in process environments still remains uncertain, again caused by the rigid characteristics of process industries (i.e. inflexible processes with high changeover times and sequence dependence). Nonetheless, the applicability in discrete sectors is straightforward. Thus, lean tools for hybrid semi-process environment, falls again in the same root-cause that inherits the clear applicability and control of the result with the uncertainty of the process environments.

1.3 Scope

The scope of this thesis is defined inside the production planning and control environment of semi-process industries. All the concepts analysed are not going further into the supply chain as it depicts a wider range of study. Within all the different lean tools, only those related or useful for the production and planning systems are defined and analysed. The applicability and interaction between all the concepts studied at the literature review are only done under the cases of process and semi-process industries. As a result, between the traditional customer interactions strategies that can be found; engineer to order (ETO), make to order (MTO), assembly to order (ATO) and make to stock (MTS), the engineer to order (ETO) typology is not analysed. Moreover, ATO strategies depict a hybrid push-pull scenario that is also not taken into account when analysing the applicability of lean tools is semi-process industries.

From a production perspective, producing high customized specific products under a project production typology, which is closely related to the ETO customer interaction, is not defined and used at this thesis as it is applied to high customized specific products which are never produced under a process manufacturing facility.

1.4 Research goal and research questions

One of the goals that seek this research is to depict a clear understanding of the manufacturing environment evolving discrete, process and semi-process industries. Secondly, after providing an overview of these environments, the research continues with a study of lean PPC tools and concepts. The aim of this research is create an understandable framework to see on which product and process characteristics, lean PPC tools are applicable at semi-process industries. These goals can be reviewed in three research questions as:

- What characterizes manufacturing environments?
- How to define the manufacturing environment of semi-process industries?
- Which lean PPC tools and concepts can be applied to the manufacturing environment of semi-process industries?

1.5 Methodology

The methodological approach of this thesis is based on a detailed literature review of manufacturing environments for discrete, process and semi-process industries on one hand, and of lean production and control methodologies on the other. Manufacturing environments are defined by the interaction of the product, process and customer. Thus, the first part of the thesis is segmented in four parts. In terms of product characteristics distinguishing between process and discrete industries. In terms of production strategies, the different environments found at the traditional product-process matrix are analyzed. In terms of customer interaction the different production driver types and CODP interactions are taken into account. Further in this first research, the framework from Jonsson and Mattsson (2003) is depicted in order to select the most important characteristics. To conclude this first part of the thesis, a characterization for semi-process environments is done by analyzing the traditional product-process matrix.

At the second part of the thesis, lean manufacturing concepts are studied and production and control systems beneath these methodologies are analyzed. Lean manufacturing tools characteristics studied and their applicability in different manufacturing environments is depicted.

Finally, by comparing semi-process industries environments with the applicability of lean PPC tools a proposal framework is created based on all the literature review. This framework provides a visual understanding of the applicability of lean PPC tools in different product and process characteristics. In addition, a more specific application of lean PPC methodologies in terms of product demand is proposed based on the literature findings.

Chapter 2 – Manufacturing environments

Introduction

Lots of different terms are used to describe manufacturing systems when identifying a specific manufacturing industry. In order to make a clear understanding this first chapter is addressed to define all the concepts related to manufacturing environments for semi-process industries.

All manufacturing industries can be classified by its manufacturing environment. Nonetheless when talking about this term two different definitions at the American Production and Inventory Control Society (APICS) dictionary (John H. Blackstone Jr., 2013, p. 98) can be found:

1. *"The framework in which manufacturing strategy is developed and implemented. Elements of the manufacturing environment include external environmental forces; corporate strategy; business unit strategy; other functional strategies (marketing, engineering, finance, etc.); product selection; product/process design; product/process technology; and management competencies".*

2. *"Whether a company, plant, product, or service is make-to-stock, make-to-order, or assemble-to-order".*

In this thesis the term "*manufacturing environment"* refers to the first definition. The second definition is understood as the customer interaction, which is introduced in the market interaction strategies point.
To develop a clear understanding of the manufacturing environments and characterize the production planning and control (PPC) system for semi-process industries, a thorough understanding of the environment in terms of customer interaction, products and transformation processes is a must. The production planning and control system exists in relation to a reality, and there must be compatibility between the reality and the PPC system. The reality can be summarized as a customer demanding a product that is produced by a process, where there is a PPC system for the planning and control of the dynamics of these entities as they interact. (Olhager & Wikner, 2000) These three aspects are not totally dependent one from another but are related. They can be used to define in different ways the environment of manufacturing industries.

The characteristics of these three entities on a company have great influence on the driver type which initiates the flow of the materials and the position of the customer order decoupling point (CODP) in the production process.(van Hoek, 2001) Thus, the three concepts of product, process and customer underline the hybridity inherent in production processes. (Noroozi & Wikner, 2014, p. 1; Semini et al., 2014, p. 3)

These three entities have been linked for manufacturing environments in the traditional product-process matrix developed by Hayes and Wheelwright (1979) The main conclusion taken from there is that the more flexible the process needs to be, the lower volume of products can be produced, and the more customisation of products is possible, thus the higher upstream on the production process the CODP should be located. (Duray, 2011; Semini et al., 2014, p. 3) However, for some manufacturing environments this classification is too generic as it does not reflect all the possible interactions of product, process and customer that can be found at the industries these days. (D. Dennis & J. Meredith, 2000; Duray, 2011)

The first of these three entities, the product or object type, defines the manufacturing process of a company and for this reason this concept is firstly analysed. Tied with that comes the differentiation between process and discrete industries. The process related with the production of the product and the flow of the materials is the second concept analysed as production strategies. Finally, the driver type or customer interaction at the production process is analysed as market interaction strategies.

Afterwards semi-process industries characteristics are analysed and the different manufacturing environments found are characterised. Finally, the three aspects studied at the first part of this chapter are connected and analysed at the semi-process industries case under the product-process matrix.

Then, this first block of the thesis will be then divided as follows:

2.1 Manufacturing processes
2.2 Production strategies
2.3 Market interaction strategies
2.4 Semi-process manufacturing environments

Before going into detail and to make sure that all the information gathered is useful, a classification framework has been depicted in order to have the specific characteristics needed to define a characteristic manufacturing environment.

The framework used to develop this classification is the one from Jonsson and Mattsson (2003). This framework has been chosen because it has all the three concepts of product, process and customer interaction well defined and distinguished. This framework has been used so far for different authors as Spenhoff, Semini, Alfnes, and Strandhagen (2014) to classify different manufacturing environments.

Based on Jonsson and Mattsson (2003) framework the main characteristics reviewed at table 1 are highlighted in order to analyse the main properties of the manufacturing environment at the production process. From Jonsson and Mattsson (2003) framework the following concepts have been eliminated as they are industry specifics and are not relevant when defining a general type of industry environment; product data accuracy, level of process planning, time distributed demand and inventory accuracy.

Table 1: Framework characteristics from Jonsson and Mattsson (2003, p. 877)

Characteristics		Description
Manufacturing process	**Manufacturing mix**	Homogeneous or mixed products from a manufacturing process perspective
	Organization and plant layout	Functional, cellular or line layout and routings. Process or product focus.
	Batch size	The manufacturing order quantity
	Number/Type of operations	Number of operations in typical routings/ Type of operations taken in the process
	Sequencing dependency	The extent to which set-up times are dependent on manufacturing sequence in work centers.
	Through-put times	Typical manufacturing through-put times
Product	**BOM complexity**	The number of levels in the bill of materials and the typical number of items on each level. (Depth and wide)
	Product Variety	The existence of optional product variants.
	Degree of value added at order entry	The extent to which detailed process planning is carried out before manufacture of the products.
	Proportion of customer specific items	The extent to which customer specific items are added to the delivered product.
Demand and market characteristics	**P/D ratio**	The ratio between the accumulated product lead-time and the delivery lead-time to the customer.
	Volume/Frequency	The annual manufactured volume and the number of times per year that products are manufactured.
	Type of procurement ordering	Order by order procurement or blanket order releases from a delivery agreement.
	Demand Characteristics	Independent or dependent demand.
	Demand type	Demand from forecast, calculated requirements or from customer order allocations.
	Source of demand	Stock replenishment order or customer order

2.1 Manufacturing process and product

2.1.1 Introduction

At the manufacturing environment, the process transformation system used is a key point in order to define manufacturing industries.

APICs dictionary describes manufacturing process as

> *"The series of operations performed upon material to convert it from the raw material or a semi-finished state to a state of further completion" or "The activities involved in converting inputs into finished goods."*

On the one hand, manufacturing processes can be arranged in different layouts; process layout, product layout, cellular layout, or fixed-position layout. The production layout is closely related to the production strategy used by every industry. On the other hand, manufacturing processes can be planned to support different customer orders: make-to-stock, make-to-order, assemble-to-order, and so forth, based on the strategic use and placement of inventories. (John H. Blackstone Jr., 2013, p. 99) Customer orders are related to the market interaction strategies.

To make a classification of the manufacturing processes two systems are identified: process manufacturing and discrete manufacturing. While discussing the differentiating characteristics of process and discrete production, the influential factor is the continuity of the object, which affects the choice of the production processes and resources (Fransoo & Rutten, 1993 ; Noroozi & Wikner, 2014, p. 5) Thereby two different types of products can be characterized:

- *Discrete products*
  Discrete means distinct solid materials that do not readily change and that maintain their solid form and shape with or without containerization. (Abdulmalek et al., 2006, p. 18; D. Dennis & J. Meredith, 2000, p. 1086)

- *Continuous or non-discrete products*
  Non-discrete materials are liquids, pulps, slurries, gases, and powders that evaporate, expand, contract, settle out, absorb moisture, or dry out. These materials change constantly and cannot be held without containerization (Abdulmalek et al., 2006, p. 18; D. Dennis & J. Meredith, 2000, p. 1086)

Authors such as King (2009) and Mikell and Groover (1980) make a differentiation of manufacturing environments in terms of process industries and assembly industries, instead of process and discrete industries. King (2009) argues that many process industries operate in batch environments with likeness to discrete parts manufacture, whilst, on the other hand, many discrete parts manufacturers share characteristics with the process industries, where high volumes and large inflexible machines with long setup and changeover times require a high level of asset utilization.

From these characteristics, Powell et al. (2010 pg.244) concludes in line with King(2009) that is clear that it is not just the continuous process industries (e.g. oil refineries, chemicals, pulp and paper) that can be classed as process-type industries. Many discrete part manufactures also share these characteristics.

At this thesis the main differentiation used will be done in terms of discrete and process industries as it shows a better differentiation and provides a greater understanding of the main process differences. It is important to high-light that semi-process industries are not more than a subgroup within process industries which are defined by the hybridity in the production process of some industries.

Table 2 shows how scholars differ when making a differentiation of manufacturing industries in different terms; process, discrete, continuous, assembly and mechanical industries.

Table 2: Manufacturing Industries terms by authors

Terms used	Authors	
Continuous/Discrete	Cleland and Bidanda (1990) Saleeshya, Raghuram, and Vamsi (2012)	
Process/Discrete	Abdullah (2003) Abdumalek et al. (2006) Jalal Ashayeri, Selen, and Teelen (1996) Dennis and Meredith (2000) Fransooo and Rutten (1994)	Lyons et al. (2013) Noroozi and Wikner (2014) Pool et al. (2011) White (1996)
Process/Assembly	King (2009) Mikell and Groover (1980)	
Process/Mechanical	Floyd (2010)	

2.1.2 Industries differentiation

At this section the general characteristics of process and discrete industries will be depicted. Note that all the concepts stated are generic concepts that cannot be taken straightforward as every industry specific environment will differ from the other.

The general characteristics of process industries are well represented in the APICS dictionary definition which has been used by many scholars (Fawaz Abdullah, 2003; D. Dennis & J. Meredith, 2000, p. 1086; D. R. Dennis & J. R. Meredith, 2000, p. 683; Fransoo & Rutten, 1993, p. 48; John H. Blackstone Jr., 2013, p. 133; Lyons et al., 2013, p. 480; White, 1996)
"Process industries are businesses that add value to materials by mixing, separating, forming, or by chemical reactions. Processes may be either continuous or batch."

In other words, process industries add value by modifying the physical or chemical properties of materials.(F Abdullah & Rajgopal, 2003, p. 2; Caputi, Coltman, & Alony, 2011, p. 335; D. Dennis & J. Meredith, 2000, p. 1086)
The definition indicates that the type of manufacturing process performed is one of the most important characteristics. Mixing, separating, forming and chemical reactions are operations that are usually performed on non-discrete products and materials. (Fransoo & Rutten, 1993, p. 48) Therefore, the process industries employ process manufacturing, with a continuous flow production approach. Nevertheless, as said before, not all the process industries use flow production as the hybridity inherent in their process let them produce in intermittent modes (e.g. batch production) (D. Dennis & J. Meredith, 2000, p. 1086)

On the other hand, discrete manufacturing is defined by (Abdulmalek et al., 2006; Cleland & Bidanda, 1990; D. R. Dennis & J. R. Meredith, 2000) as:

"Manufacturing adding value by assembly, handling, and performing of discrete components and the processed entities maintain shape and form without containerization".

Discrete manufacturing is based at the production of distinct items. (John H. Blackstone Jr., 2013, p. 14) Typical examples of discrete manufacturing industries products are automobiles, appliances or computers. (Abdulmalek et al., 2006, p. 4; John H. Blackstone Jr., 2013, p. 49; White, 1996, p. 1367)
Lyons et al. (2013, p. 480) defines discrete manufacturing as industries producing countable, distinguishable products. Discrete manufacturing is identifiable in each of the first four process types (project, job shop, batch and repetitive). Most manufacturing is discrete in nature and there is a diverse array of products produced in discrete environments. (Lyons et al., 2013, p. 480)

Related with the manufacturing process, the manufacturing mix for process industries tends to be low, with small mix flexibility (Pool et al., 2011) having mainly homogeneous products. On the other hand, manufacturing mix for discrete industries will be mainly high, with large mix flexibility and mixed product for discrete production (Pool et al., 2011)
Process industries have process layout with large installations and inflexible equipment. Typically process industries have flow shop production type environments (Abdulmalek et al., 2006, p. 20; Fawaz Abdullah, 2003, p. 30) with line layout in continuous or connected flow. (Mahapatra & Mohanty, 2007, p. 20)

However, in some typical process industries, although there may be some degree of continuous processing, often the production is performed in batches. (Powell et al., 2010 pg.244) A job-shop layout can also be an occurrence for some process industries albeit this last is a relatively rare industrial occurrence (Lyons et al., 2013, p. 480)
On the other hand, discrete industries usually tend more toward the job shop end of the spectrum (Taylor, Seward, & Bolander, 1981, p. 11) using both product and process layout with functional, cellular and line layouts. High flexible process and equipment leads to more product based layouts.

Process industries are commonly defined with high volume of production, low variety of products and inflexible production systems. (Abdulmalek et al., 2006, p. 18; Fawaz Abdullah, 2003, p. 35; John H. Blackstone Jr., 2013, p. 133) Thus tend to use fixed, large batch sizes in their processes. On the contrary, discrete industries use variable batch sizes as their production can go from a wider spectrum of variety and volume products (Pool et al., 2011, p. 199)

Process industries have typically long runs of production (Pool et al., 2011, p. 199), with small number of workstations (Mahapatra & Mohanty, 2007, p. 20) and fixed routings. These large production flows, can present significant storage handling and distribution challenges for this industries. (Fransoo & Rutten, 1993, p. 48; White, 1996, p. 1367) Discrete industries have commonly short runs, with many workstations due to jumbled and disconnected flow (Pool et al., 2011, p. 199)

Sequence dependency is high for process industries due to WIP, volume and sequence restrictions (Pool et al., 2011) As production is taken mostly in fixed routings with specialized equipment, long setup times are required (Abdulmalek et al., 2006). Low sequence dependency is found in discrete industries due to disconnected and jumbled flow processes (King, 2009) giving ample capacity of production and small changeover times. (Abdulmalek et al., 2006; Pool et al., 2011)

Throughput times are mainly variable in both industries, ranging from low to high. Nevertheless, one can generalize with short throughput times for process industries and long for discrete. Fransoo and Rutten (1993)

In terms of the product, the process industry can be thought of as producing materials rather than producing items as in the discrete manufacturing industry. (F Abdullah & Rajgopal, 2003, p. 2) BOM is usually shallow for process industries. Ranging from a small to large variety of raw materials (F Abdullah & Rajgopal, 2003) having a divergent materials flow structure (V,T) (Fransoo & Rutten, 1993). Product structure for discrete industries is usually deep (Lyons et al., 2013) with assembled BOM and convergent materials flow structure (A,X) (Fransoo & Rutten, 1993)

Process manufacturing environments are commonly defined as having a low product variety. (Abdulmalek et al., 2006, p. 18; Fawaz Abdullah, 2003, p. 35; John H. Blackstone Jr., 2013, p. 133) Most manufacturing is discrete in nature and therefore there is a high variety of products produced in discrete environments. (Lyons et al., 2013, p. 480)

The extent to which detailed process planning is carried out before manufacture of the products tends to be often high (MTS) but sometimes lower (ATO) for process industries.

(Noroozi & Wikner, 2014) Thus, proportion of customer specifications are often low (MTS), but can some degree of customization (ATO). (Pool et al., 2011)

Discrete environments face a wider range where VAOE is often low (MTO or ATO) although it can also be high (MTS). Proportion of customer items in normally high in discrete environments but can range from low (MTS) to high (MTO) in most environments. This is closely related with the P/D ratio that tends to be >1 and sometimes <1 in process environments and normally <<1 in discrete, MTO.

Demand for process industries are usually stable and regular, thus easy to be forecasted. The use of blanket orders is often used in order to reduce costs. The demand type for process industries is mainly forecast based as products are not customized and demand is dependent, thus easy to be forecasted. It is not usual to have customer order demand. (Noroozi & Wikner, 2014) Moreover, the source is mainly from stock replenishment (Noroozi & Wikner, 2014). In discrete industries demand is mostly and customer order type as products are normally highly customized. (Noroozi & Wikner, 2014) Demand is independent for each product and variable. Consequently orders are individual and customer specific.

The process industry is not one industry but a collection of industry types. (Lyons et al., 2013, p. 475) The Institute of Operations Management provides a list of characteristic process manufacturing industries that includes chemicals, bio-technology, food and beverages, paper and board, textiles, glass, rubber and plastics, semi-conductors and primary metals.(Lyons et al., 2013, p. 481) An equivalent list for typical discrete manufacturing includes automotive, domestic appliances, electronics, telecommunications equipment, machinery and capital equipment. (Abdulmalek et al., 2006, p. 4; John H. Blackstone Jr., 2013, p. 49; Lyons et al., 2013, p. 481; White, 1996, p. 1367)

Table 3 depicts the main differences between process and discrete industries using the framework proposed at the beginning of this thesis.

Table 3: Differences between process and discrete industries

Characteristics		Process Industries	Discrete Industries	Source
Manufacturing process	**Manufacturing mix**	Low to high mix	High	Fawaz Abdullah (2003)
	Batch size	Fixed, large	Variable volumes	Fawaz Abdullah (2003) Abdulmalek et al. (2006)
	Organization and plant layout	Process based Batch, line and continuous	Product and process layout Job shop, batch and line	Lyons et al. (2013) Mahapatra and Mohanty (2007) Noroozi and Wikner (2014)
	Number/Type of operations	Long runs Fixed routing Small number of workstations	Short runs Variable routings Many workstations	Mahapatra and Mohanty (2007) Pool et al. (2011) Jalal Ashayeri, Teelen, and Selen (1995)
	Sequencing dependency	Sequence restrictions Long setup times	Small change-over times Short set up times	Jalal Ashayeri et al. (1995) Pool et al. (2011) Abdulmalek et al. (2006)
	Through-put times	Short	Long	Fransoo and Rutten (1993) Jalal Ashayeri et al. (1995)
Product	**BOM complexity**	Small to large variety of raw materials Shallow product structure Few input raw materials Divergent flow (V,T)	Deep product structure Assembled BOM Convergent flow (A,X)	Fawaz Abdullah (2003) Fransoo and Rutten (1993) Lyons et al. (2013) Noroozi and Wikner (2014) Jalal Ashayeri et al. (1995)
	Product Variety	Often low, increasingly high	High	Abdulmalek et al. (2006) Jalal Ashayeri et al. (1995) Lyons et al. (2013) Noroozi and Wikner (2014) Pool et al. (2011) White (1996)
	Degree of value added at order entry	Often high MTS/ Sometimes lower ATO	Often low MTO,ATO / Sometimes high MTS	Noroozi and Wikner (2014)
	Proportion of customer specific items	Often low	From low to high	Pool et al. (2011)
Demand and Market characteristics	**P/D ratio**	Often P/D >1 (MTS, ATO) Sometimes P/D < 1 (ETO, MTO)	Often P/D < 1 or P/D =1 (ETO, MTO) Sometimes P/D >1 (MTS, ATO)	Pool et al. (2011)
	Volume/Frequency	High volume for few SKUs Low volume for many SKUs	Low volumes	Fawaz Abdullah (2003) Jalal Ashayeri et al. (1995)
	Type of procurement ordering	Blanker order for high volume products, procurement order for low volume products	Procurement order	-
	Demand Characteristics	Dependent, stable demand per blend	Independent Variable demand per SKU	Pool et al. (2011)
	Demand type	Forecast demand and calculated requirements	Customer order demand	Noroozi and Wikner (2014)
	Source of demand	Stock replenishment order	Customer order	Jalal Ashayeri et al. (1995) Noroozi and Wikner (2014)

2.2 Production strategies

2.2.1 Introduction

The production strategy used in a manufacturing facility is the fundamental characteristic of the operations performed and the manufacturing strategy followed. Production strategies are typically determined by the required volume and variety mix in order to satisfy a market. (Jagdev, Brennan, & Browne, 2004, p. 115; Lyons et al., 2013, p. 480)

With respect to traditional production strategies, the volume of parts can be divided into three distinct categories: job-shop production, batch production and mass production. Beneath this classification five primary production strategies in terms of different product flow are distinguished: project, process job shop, batch, product line and continuous line. (Fawaz Abdullah, 2003, p. 30; Jagdev et al., 2004, p. 115; Lyons et al., 2013, p. 480) Typically, volume of products increases and variety decreases from the project process type through to the continuous flow type. (Lyons et al., 2013, p. 480)

Table 4: Production strategies

Group	Subgroup
Job-shop production	Project
	Process job-shop
Batch production	Batch shop
Mass production	Product flow line
	Continuous flow line

The main characteristics for the traditional production strategies are summarized in table 5.

Traditional production strategies for manufacturing environments have been based on the product process matrix developed by Hayes and Wheelwright (1979). This framework links product structure with process structure (see figure 1). It has four differentiated stages for the process, jumbled flow, disconnected line flow, connected line flow and continuous flow. This stages are inherent connected with the flexibility of the process (which provides variety) and the cost of the products (achieved by economies of scale with high volume production) (Duray, 2011, p. 34)

Table 5: Process flow matrix proposal developed from the literature review

Characteristics	Production flow	Job-shop		Batch production	Mass production Flow-shop		Source
		Project	Process		Product line	Continuous line	
Manufacturing process	**Manufacturing mix**	Very high	High	Moderate	Low	Very low	[10]
	Batch size	Small size	Small products	Medium size lots	Large size lots	Large product	[1] [5] [7]
	Organization and plant layout	Functional departments	Functional departments	Product line	Product line	Product line	[1]
		No flow	Jumbled flow	Disconnected, with some dominant flows	Connected line	Continuous line	[1] [7]
		Product	Product	Process	Process	Process	[11]
		Variable routings	Variable routings	Regular intervals	Standard and fixed routings	Standard and fixed routings	[1] [3] [11]
	Number/Type of operations	Very high	High	Moderate	Low	Very low	[9]
	Sequencing dependency	One time	One time	Intermittent	Intermittent	Continuous	[1] [3] [7] [8]
	Through-put times	Variable	Low	Medium	High	Very high	[4]
	Equipment	Multipurpose equipment and Multi-skilled workers	General purpose machines and humans	General-purpose machines	Highly dedicated and automated machines	Expensive and special-purpose machines	[1]
	Flexibility	Very high	High	Medium	Low	Very low	[1] [2] [7] [8]
Product	**BOM complexity**	Very high	High	Medium	Low	Very low	[1] [3] [4] [7]
		Convergent (A, X)	Convergent (A, X)	Convergent (A, X)	Mix (A, V, X, T)	Divergent (V, T)	[5]
	Product variety	Unique	High	Medium	Low	One	[1] [6]
	Degree of value added at order entry	Very high	High	Medium	Low	Very low	[10]
	Proportion of customer specific items	Very high	High	Medium	Low	Very low	[10]

[1] Fawaz Abdullah (2003, p. 33)
[2] Abdulmalek et al. (2006)
[3] Cleland and Bidanda (1990, p. 243)
[4] Groover Jr (1980)
[5] Jagdev et al. (2004)
[6] John H. Blackstone Jr. (2013)
[7] Needy and Bidanda (2001)
[8] Noroozi and Wikner (2014)
[9] Mahapatra and Mohanty (2007)
[10] Olhager, Rudberg, and Wikner (2001)
[11] Taylor et al. (1981)

Duray (2011), D. Dennis and J. Meredith (2000), Jonson and Mattson, Ahmad and Schroeder (2002) and Johansson and Olhager (2006) agree to say that the classification of Hayes and Wheelwright (1979) no longer map all the product-process possibilities of the manufacturing industries.
Ahmad and Schroeder (2002) makes an empirical study of the product-process matrix to highlight that off-diagonal structures are possible and distinguish between four main groups of production with different subtypes.
Process industries production strategies have been studied empirically by D. Dennis and J. Meredith (2000). Their approach distinguishes the characteristics of different types of manufacturing industries, being a further detail of propositions by Fransoo and Rutten (1993). D. Dennis and J. Meredith (2000) classification is made distinguishing Intermittent, Hybrid and Continuous processes industries within seven subgroups.
On the other hand, from a manufacturing planning and control perspective, Jonsson and Mattsson (2003) propose a differentiation between four different types of environments.

To see which are the main differences and which off-diagonal positions are possible all these different classifications are located in the product-process matrix. Figure 2 shows all the different classifications reflected in numbers. Each number corresponds to a singular classification which is reviewed in table 6. These numbers being inside the same square are meant to have same product volume and customisation as well as to share the same amount of process flexibility. Even though, the subgroups cannot be understood as being the same production strategies.

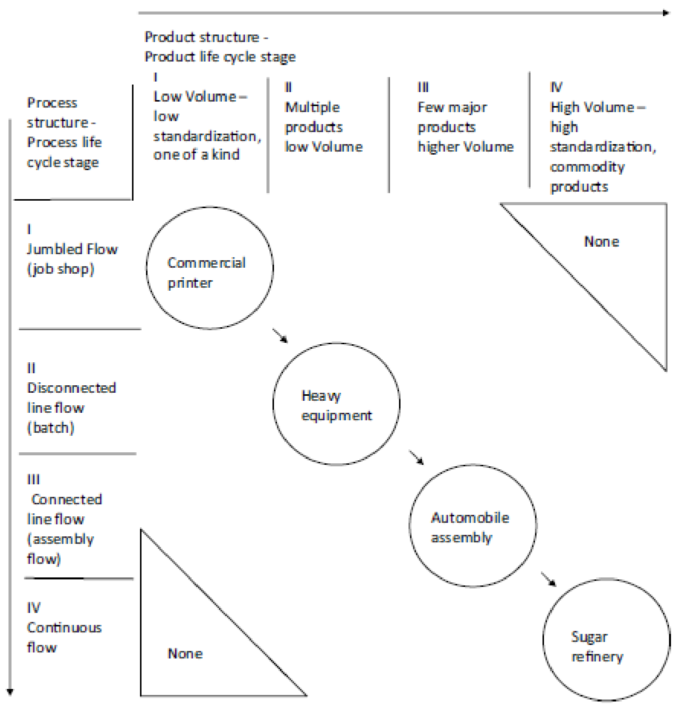

Figure 1: Traditional product-process matrix by Hayes and Wheelwright (1979) in Duray (2011)

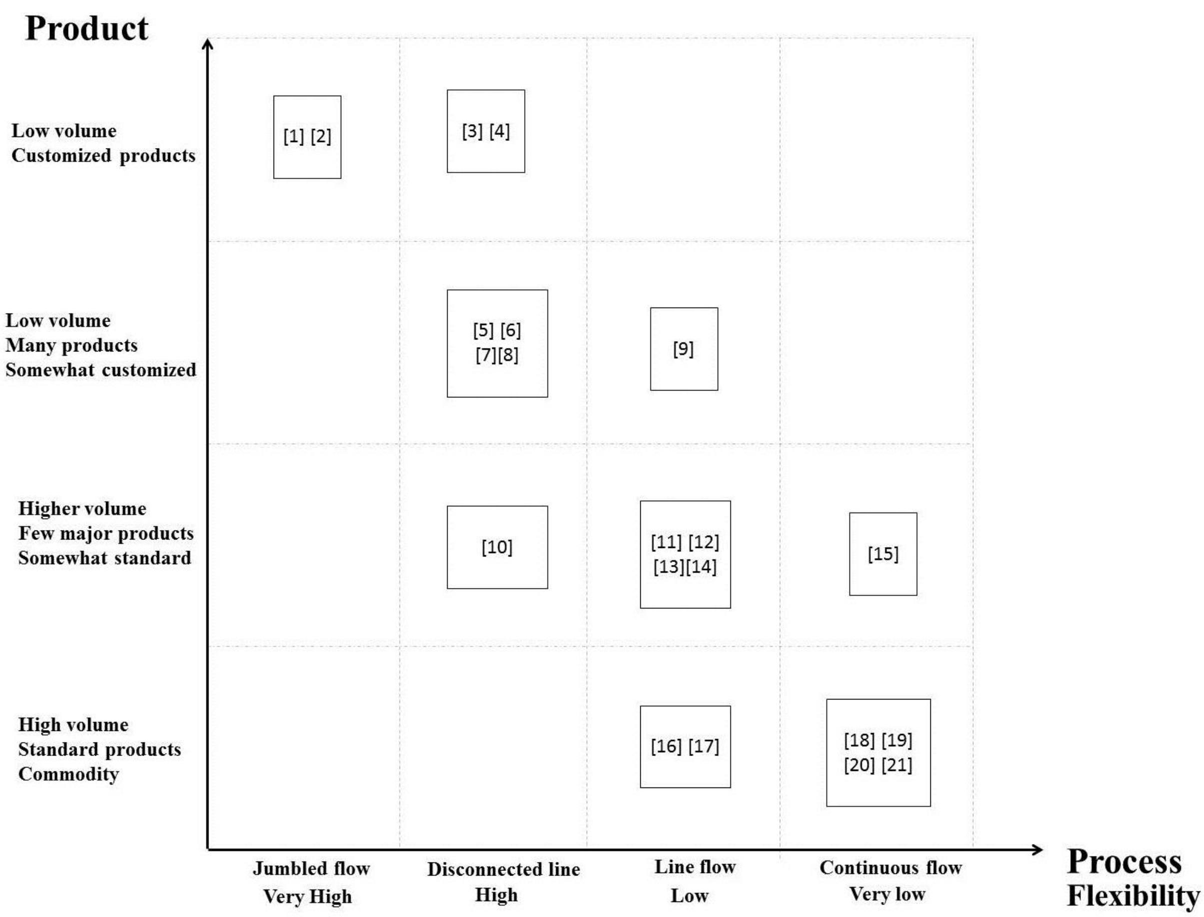

Figure 2: Product-process matrix with environments differences

Looking at the distribution of the different subtypes one can see that even having distinct properties more than the half of the subgroups is located at the main diagonal. That is why some scholars as Duray (2011) or Johansson and Olhager (2006) propose a third dimension for the matrix (e.g. distinguishing between different levels of product variety) in order to highlight all this differences.

Nevertheless, from the results of this classification it is clear that off-diagonal positions are real possibilities for manufacturing industries. For example, continuous flow manufacturing systems can produce with some product customisation and product diversity. (Ahmad & Schroeder, 2002) At the other side of the spectrum low volume, customised products are not only possible to produce under a job-shop environment, but also with a batch production of customized products. At the centre of the matrix, disconnected and line flows are the ones having a broader range of custom possibilities.

Table 6: Product-process matrix subtypes

Num.	[1]	[2]	[3]	[4]	[5]	[6]	[7]
Name	**Job-shop**	**Process Job shop**	**Custom bleding**	**Large batch customizers**	**Batch shop**	**Fast batch**	**Batch production of stand. Prod.**
Prop	Low volume High variety Variable routings High flexibility General purpose equipment	Very high flexibility Highly jumbled process pattern Long run times Extensive flexibility Highly complex products One at a time	One pot blending production Simple formulation with little chemical reactions Great customization General purpose equipment High flexibility	Batch producers High customised	Medium volume Medium variety Regular intervals Medium flexibility General purpose equipment	General purpose equipment High flexibility Multiples batches Batch type Short run time	Medium complex. MTS Many products Large freq. Cellular/functional layout
Source	Fawaz Abdullah (2003) Jagdev et al. (2004) Lyons et al. (2013)	D. Dennis and J. Meredith (2000)	D. Dennis and J. Meredith (2000)	Ahmad and Schroeder (2002)	Fawaz Abdullah (2003) Jagdev et al. (2004) Lyons et al. (2013)	D. Dennis and J. Meredith (2000)	Jonsson and Mattsson (2003)

Num.	[8]	[9]	[10]	[11]	[12]	[13]	[14]
Name	**Large batch customizers**	**Custom hybrid**	**Small batch**	**Product line**	**Stock hybrid**	**Configure to order**	**Repetitive manufacturers**
Prop	Line flow Somewhat customised	Low flexibility Customized products Large variety of raw materials Simple formulation	Batch production Somewhat standard	High volume Low variety Low flexibility Fixed routings Dedicated equipment	Low product variety Low flexibility	Medium complex. ATO/MTO Volume Many Medium freq. Cellular/line layout	Line flow Somewhat standard prod.
Source	Ahmad and Schroeder (2002)	D. Dennis and J. Meredith (2000)	Ahmad and Schroeder (2002)	Fawaz Abdullah (2003) Jagdev et al. (2004) Lyons et al. (2013)	D. Dennis and J. Meredith (2000)	Jonsson and Mattsson (2003)	Ahmad and Schroeder (2002)

Num.	[15]	[16]	[17]	[18]	[19]	[20]	[21]
Name	**Mass standard to option providers**	**Repetitive mass production**	**Repetitive manufacturers**	**Continuous flow line**	**Multistage continuous**	**Rigid continuous**	**Mass standard to option providers**
Prop	Continuous flow Standard with customer options	Low complex. MTS/ATO Pull production Line layout	Line flow High standard prod	High volume Low variety Inflexibility Fixed routings Special-purpose equipment	Sequence dependency Low flexibility Few routing Long product run times	Sequence dependency Very low flexibility Few routing Long product run times	Continuous flow High standardized products
Source	Ahmad and Schroeder (2002)	Jonsson and Mattsson (2003)	Ahmad and Schroeder (2002)	Fawaz Abdullah (2003) Jagdev et al. (2004) Lyons et al. (2013)	D. Dennis and J. Meredith (2000)	D. Dennis and J. Meredith (2000)	Ahmad and Schroeder (2002)

To conclude this section, from the traditional approach some objectives can be highlighted at every different production system. Thus, for job-shop and batch production (intermittent production) the main objectives will be related with the time-cost of the processes.

- The first objective is to reduce setup time. This is not important for mass production because the machine is seldom undergoing setup. However, in intermittent production, parts spend the majority of their life waiting for other jobs to finish and waiting for the machines to be set up.

- The second objective is to reduce the processing time. A reduction in processing time will reduce the overall time to produce the part. However, the percentage decrease in total time will not be nearly as large as with mass production.

- The last and also important objective of job shop production is to reduce WIP (work in process). This can be accomplished by scheduling the workload to maximize machine utilization, minimize waiting time, and minimize the number of pre-empted jobs.

Whereas the objectives related with mass production systems are as follows.

- The first is to reduce the operation cycle time. In mass production, a part spends a greater percentage of the time actually being processed than in the other strategies. Therefore, if the operation cycle time can be reduced, savings can be realized.

- The second mass production objective is to increase the reliability of the system. Since in most highly automated systems the whole line can be stopped if a single station breaks down, it becomes very important for each station to be highly reliable. The system reliability can be increased by increasing the reliability of the individual operations or by reducing the number of operations in the product line. Since the line is rarely changed, the time required to set up the line is not as important as it is with the other strategies. Minimizing the setup time is not an important objective.

2.3 Market interaction strategies

2.3.1 Introduction

At the production processes the market interaction with the production process has two big different typologies: Forecast driven and Customer driven.

Forecast driven production is based on estimations of product demand volume and variability. These systems usually compete on low prices so performance measures such as cost and productivity are important (Olhager, 2003). This implies mass production, economy of scale and high utilization of the equipment. In addition, due to market expectations of very short lead-times, these companies keep inventories of end products to fulfil the demand (Olhager et al., 2001; Olhager, Selldin, & Wikner, 2006). This inventory is used to absorb the demand fluctuations as well. Therefore in these companies, the decisions are taken about the level of production, lot sizes and the inventory of product families (Soman, van Donk, & Gaalman, 2004)

On the other hand, customer driven production is based on the customer order to deal with the demand volume and variability of the products. Customer order companies compete on design, flexibility and delivery speed. The important performance measures for these companies are flexibility and delivery lead-times. Hence, keeping free capacity and consequently low utilization of the equipment will be a keep point. Based on the expected lead-time from the market and in order to keep the utilization at an accepted level, these companies should decide about the backlog level instead of inventory (Olhager et al., 2001; Olhager et al., 2006)

The planning and control concepts in a hybrid forecast driven – customer driver system is not straightforward. The challenges include the cost of low utilization of equipment, the possibility of decoupling the production process and adding buffers, the capacity of the buffers and the selection of intermediate products.(Caux, David, & Pierreval, 2006)

The customer order is an order from a customer for a particular product or number of products. It is often referred to as an actual demand to distinguish it from a forecasted demand. On the other hand, the decoupling point is defined as being the locations in the product structure or distribution network where inventory is placed to create independence between processes or entities. Selection of decoupling points is a strategic decision that determines customer lead times and inventory investment. (John H. Blackstone Jr., 2013, pp. 39-41; Wikner & Rudberg, 2005b, p. 211) Therefore, the customer order decoupling point (CODP) is the point in the material flow where the product is tied to a specific customer order. (John H. Blackstone Jr., 2013; Olhager, 2003, p. 320; 2010, p. 863)

The CODP acts as a decoupling mechanism separating the customer order-driven activities (downstream the CODP) from those that are forecast-driven (upstream the CODP) (Gosling & Naim, 2009, p. 743; Olhager, 2003, p. 320; 2010, p. 863; Sun, Ji, Sun, & Wang, 2008, p. 943; Van Donk, 2001, p. 298; Wikner & Rudberg, 2005a, p. 625)

Or, in other words the decoupling point is the point that indicates how deeply the customer order penetrates into the goods flow.(Van Donk, 2001, p. 298; Wikner & Rudberg, 2005b, p. 212) This is not only important for the distinction of different types of activities, but also for the related information flows and the way the goods flow is planned and controlled. (Van Donk, 2001, p. 298)

In congruence with the latter definition, the CODP is sometimes referred to as an order penetration point (OPP) by authors as Wikner and Rudberg (2005b, p. 212).

In both Wikner and Rudberg's articles (Wikner & Rudberg, 2005a, p. 625; 2005b, p. 212) the interaction strategies classified in relation with the CODP is based on the concept of the P:D ratio, introduced by Kemppainen, Vepsäläinen, and Tinnilä (2008). In the P: D ratio, both 'P' and 'D' are lengths of time, where 'P' represents the production lead-time and 'D' represents the delivery lead-time (the time from order to delivery). Based on the ratio of 'P' divided by 'D' one can determine the amount of planning and production that needs to be based on speculation, and the amount that can be based on customer orders. Hence, the P: D ratio corresponds to different positioning of the CODP as visualized in figure 3 (Hoekstra and Romme, 1992; Browne et al., 1996; Higgins et al., 1996; Sacket et al. 1997; Wortmann et al., 1997; Mather, 1999).

The different manufacturing situations are related to the ability of the manufacturing operations to accommodate customizing or a wide product range (Olhager, 2003, p. 320)

The traditional customer order decoupling point (CODP) typology contains four typical cases, i.e. engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO) and make-to-stock (MTS) (Olhager, 2003, p. 320; 2010, p. 864; Semini et al., 2014, p. 2; Wikner & Rudberg, 2005a, p. 625; 2005b, p. 212)

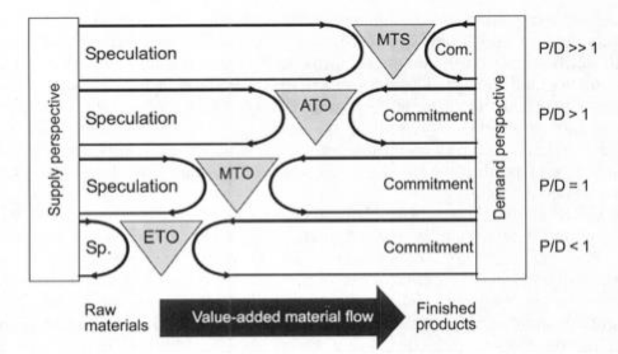

Figure 3: CODP strategies by Wikner and Rudberg (2005a)

Since the CODP provides a decoupling point between upstream and downstream operations. Quality planning, control and improvement will focus on maintaining efficient processes for upstream operations, whereas the product delivered to the customer is the main planning object for post-CODP operations. (Olhager, 2003, p. 324) Operations upstream the CODP have to successfully provide to the market the right products in the right quantities at the right cost level at the CODP inventory position. With this in place, the downstream operations have the prerequisites for providing the marketplace with customized products in a timely and effective manner. (Olhager, 2010, p. 867)

Olhager (2010) emphasizes the strategic importance of setting the CODP appropriately, which has a significant effect on cost, lead-time, flexibility, and other performance objectives. Wikner and Rudberg (2005a) conclude that the CODP is an important concept as customer focus increases and competition puts pressure on competitive priorities at the same time. (Semini et al., 2014, p. 3)

2.3.2 CODP divider

After CODP (downstream)

Real customer orders dominate downstream the CODP (Olhager, 2010, p. 864) so activities are driven by specific customer's request. (Semini et al., 2014, p. 2; Wikner & Rudberg, 2005a) The higher upstream the CODP is positioned (towards the ETO end of the scale) the more activities can be based on actual customer orders and the more specialized the product can be, and the more flexibility is needed. (Semini et al., 2014, p. 2; Wikner & Rudberg, 2005a, p. 626) This will allow a higher degree of customization, reduced reliance on forecasts, and reduced inventories. (Semini et al., 2014, p. 2) An agile supply chain would be the more suitable choice for downstream operations. (Mason-Jones, Naylor, & Towill, 2000; Olhager, 2010, p. 864; Wikner & Noroozi, 2014; Wikner & Rudberg, 2005b) Therefore, the downstream operations need the flexibility inherent in a job shop (i.e. a process layout and a process facility focus). (Olhager, 2003, p. 323)
Push MTO typology is typically required after the CODP due to customized features and low volumes per product (Olhager, 2010, p. 864) The main competitive priority that is directly related to the position of the CODP is delivery speed. If delivery speed is an order winner, the CODP should be positioned closer (in terms of time) to the final goods inventory than that of the competitors. Customers expect some products to be available off the shelf at any time, forcing the manufacturer to an MTS policy. (Olhager, 2010, p. 864)

Before CODP (upstream)

Upstream the CODP the activities are performed to forecast (on speculation) having a forecast-driven material flow (Olhager, 2010, p. 864; Wikner & Rudberg, 2005a, p. 624) At this stage, standard products or parts are produced before an actual customer has requested them (Semini et al., 2014, p. 2) as they are based on forecasts and are more or less independent from irregular demands in the market. (Van Donk, 2001, p. 298)
Volumes are typically sufficiently high before the CODP to make MTS/pull possible (Olhager, 2010, p. 864) Pre-CODP operations focus on maintaining an optimal mix and optimal inventory levels at the CODP. (Olhager, 2003, p. 323) Since pre-CODP operations are forecast-driven and need not focus on delivery speed, resource capacity can be reduced and optimized. Thus, focus moves to price competition via cost efficiency with respect to capital tied up in capacity and inventories. (Olhager, 2003, p. 323)
A flow-oriented production process is more applicable for upstream operations since the number of products is limited (i.e. a product layout and a product facility focus) (Olhager, 2003, p. 323) A lean supply chain should be applied upstream the CODP. (Mason-Jones et al., 2000; Olhager, 2010, p. 864; Wikner & Noroozi, 2014; Wikner & Rudberg, 2005b)
A downstream shift of the CODP can lead to shorter lead times, higher delivery reliability, and lower cost. (Semini et al., 2014, p. 2) The further downstream the CODP is positioned, the more of value-adding activities must be carried out under uncertainty (Wikner & Rudberg, 2005a, p. 626)

Differences

Table 7 summarizes the main differences between both two environments, before and after the CODP at the production process.

Table 7: Characteristics before and after the CODP

Characteristics		Before CODP (upstream)	After CODP (downstream)	Source
Manufacturing process	**Manufacturing mix**	Predetermined, narrow	Wide	*Olhager (2003)*
	Organization and plant layout	Product focus	Process focus	*Olhager (2003)*
		Line, high-volume batch	Job shop, low-volume batch	*Olhager (2003)* *Olhager (2010)*
	Batch size	High volume	Low volume	*Olhager (2003)*
	Through-put times	High	Low	*Olhager (2003)*
	Flexibility	Low	High	*Olhager (2003)*
Product	**BOM complexity**	Low	High	*Olhager (2010)*
	Product variety	Low Standard components	High Special, fully customized	*Olhager (2003)* *Olhager (2010)*
	Degree of value added at order entry	MTS/ATO	MTO/ETO	*Olhager (2010)*
	Proportion of customer specific items	Low	High	*Olhager (2010)*
Demand and Market characteristics	**P/D ratio**	>>1/>1	=1/<1	*Wikner and Rudberg (2005b)* *Wikner and Rudberg (2005a)*
	Volume/Frequency	High volume	Low volume	*Olhager (2003)* *Olhager (2010)*
	Demand Characteristics	Volatile/Unpredictable demand	Predictable demand	*Olhager (2003)* *Olhager (2010)*
	Demand type	Forecast	Customer order	*Olhager (2010)* *Semini et al. (2014)* *Van Donk (2001)* *Wikner and Rudberg (2005a)*
	Source of demand	Stock replenish	Customer demand	*Olhager (2010)* *Semini et al. (2014)* *Van Donk (2001)* *Wikner and Rudberg (2005a)*

2.3.3 CODP strategies

Based on the P:D ratio, one can determine the amount of planning and production that needs to be based on speculation (forecast), and the amount that can be based on customer orders. (Wikner & Rudberg, 2005a, p. 625)

Make to stock (MTS):

APICS dictionary and some scholars (John H. Blackstone Jr., 2013, p. 97; Wikner & Rudberg, 2005b, p. 214) refers to either make-to-stock (MTS) or produce-to-stock (PTS) as

> *"A production environment where products can be and usually are finished before receipt of a customer order. Customer orders are typically filled from existing stocks, and production orders are used to replenish those stocks".*

Normally firms producing with high-volume standardized products are assumed to utilize make-to-stock approaches. (Wikner & Rudberg, 2005a, p. 626) This approach is based on forecast actions where the production happens if the necessary information is triggered and the workstation is free.(Sun et al., 2008, p. 944) An organization must try to predict what the customers want, and hopefully someone will buy what is produced. (Wikner & Rudberg, 2005b, p. 213) Whilst an MTS system offers quick product delivery times, the disadvantages highlighted by Jagdev et al. (2004, p. 119) of this system include high inventory costs and standardized products.

Assembly to order (ATO):

APICS dictionary (John H. Blackstone Jr., 2013, p. 8) defines Assemble-to-order (ATO) or finish to order (FTO) as

"A production environment where a good or service can be assembled after receipt of a customer's order. Receipt of an order initiates assembly of the customized product. This strategy is useful where a large number of end products (based on the selection of options and accessories) can be assembled from common components".

Assemble-to-order interaction takes places where the decoupling point is located at the final assembly stage. (Gosling & Naim, 2009, p. 744; Olhager, 2003, p. 320) At the ATO strategy, standard components are produced to stock and assembled based on specific customer orders. (Semini et al., 2014, p. 3; Wikner & Rudberg, 2005b, p. 213)

Make to order (MTO):

APICS (John H. Blackstone Jr., 2013, p. 97) defines either make-to-order (MTO) or produce-to-order (PTO) as

"A production environment where a good or service can be made after receipt of a customer's order. The final product is usually a combination of standard items and items custom-designed to meet the special needs of the customer".

Make-to-order interaction is where the decoupling point is located at the fabrication and procurement stage (Gosling & Naim, 2009, p. 744; Olhager, 2003, p. 320) At MTO, the design is ready, but physical production only starts after receiving a customer order (Semini et al., 2014, p. 3) Firms with many low-volume, customized products are expected to choose a make-to-order, time-phased, and push approaches. (Wikner & Rudberg, 2005a, p. 626) MTO means to take actions based on the request or actual customer order. (Olhager, 2010)

Differences

Table 8 summarizes the main differences between the different CODP scenarios.

Table 8: Comparison of the different customer order scenarios from Jagdev et al. (2004, p. 119)

	Characteristic	MTS	ATO	MTO
Product	**Degree of value added at order entry**	Low / distant	Primarily at sales level	Engineering and sales level
	Delivery time	Short	Medium	Variable
	Production volume of each sales unit	High	Medium	Low
	Product variety	Low	Medium	High
	Order promising (based on)	Available finished goods inventory	Availability of components and major subassemblies	Capacity (manufacture, engineering)
Demand and marketing characteristics	**Demand type**	Forecast	Forecast and Backlog	Backlog and Orders
	Production characteristics	Safety stocks of sales units	Over-planning of components and sub-assemblies	Considerable uncertainty exists

Analysing the environments where every CODP strategy would fit, the product-process matrix can be a guide, see figure 4. The selection of every CODP would not only depend on the process but also on the product demand. Therefore, this framework is not more than a proposal based on the most common CODP approaches for every distinct product tape and process type.

The traditional product-process matrix is linked with the CODP assuming that job-shop processes will use a MTO approach, whereas batch-shop will be mostly ATO and flow-shop MTS. (Duray, 2011, p. 34; Olhager et al., 2001, p. 222) However, it is clear that not all industries approaches will be under this classification.
There exists a trend, according to which process industries tend to move away from make-to-stock and toward make-to-order strategies, while offering more diversity, customized line of products. (Crama, Pochet, & Wera, 2001) For example, the printing industry is based on repetitive manufacturing with high volume production and usually has a MTO strategy. (Duray, 2011, p. 34)
Thus, a proposal of alternatives is done. (see figure 4)

- Low volume customized products produced in job-shop environments with jumbled flow would tend to be produced under a customer driven, MTO strategy (Wikner & Noroozi, 2014; Wikner & Rudberg, 2005a, p. 626). ATO with disconnected flow. However, a MTS strategy would be a really strange occurrence.
- Products ranging from low to high volume with different variety and some customization can handle any of the three CODP strategies. Which one could fit better would depend again of both specific product demand and process characteristics.
- On the other hand, production of high volume standardized products will mainly be done under a MTS strategy. (Wikner & Rudberg, 2005a, p. 626) However, if production is done in a line the ATO strategy can be a possibility.

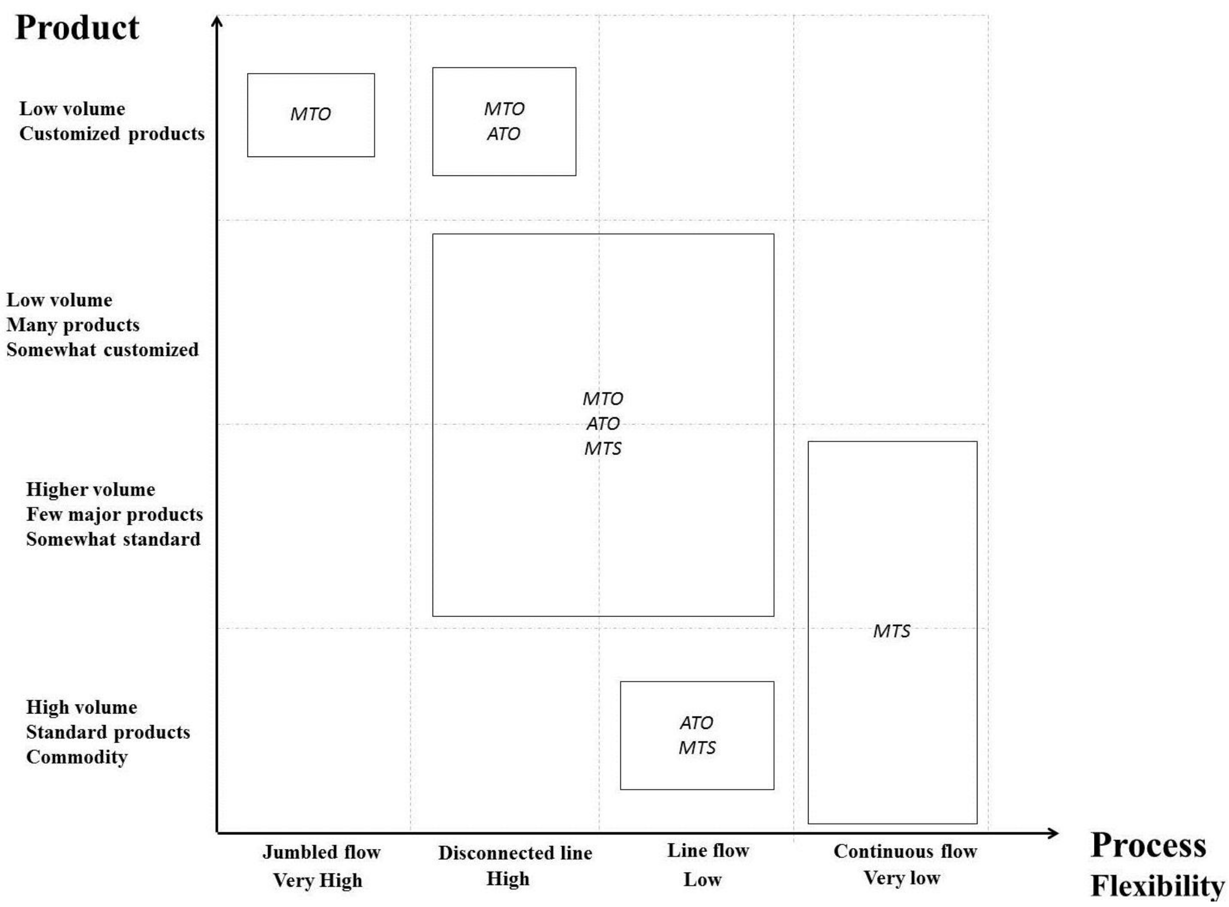

Figure 4: Product-process matrix with CODP interaction

2.4 Semi-process industries

2.4.1 Semi-process industries definition

Process industries have normally been lumped together on the basis of the fact that they are designed to produce non-discrete products. (Fawaz Abdullah, 2003, p. 30; F Abdullah & Rajgopal, 2003, p. 2) As a result, people have often ignored the distinct characteristics of the different types of process industries. While the process sector as a whole shares much in common, there are unique characteristics that are product specific. Defining the entire process industry solely based on the fact that it produces non-discrete material displays a simplistic understanding of this sector. (Fawaz Abdullah, 2003, p. 30; F Abdullah & Rajgopal, 2003, p. 2) While almost all process industries use non-discrete materials, many of them also use discrete materials. (Fawaz Abdullah, 2003, p. 30)
Almost all process industries are typically described as being purely continuous. In fact, almost all of these manufacturing systems are actually hybrids. By hybrid it is meant that their non-discrete units eventually become discrete at some point during the manufacturing process (Abdulmalek et al., 2006, p. 21; F Abdullah & Rajgopal, 2003; D. Dennis & J. Meredith, 2000, p. 1088; Lyons et al., 2013, p. 481)
This hybridity can also be seen when the production of an item involves both continuous and discrete operations as it happens in many industries within the process sector. (Fawaz Abdullah, 2003, p. 57) Thus, within a continuous process-manufacturing environment, almost always, discrete parts are produced at some point of the process, for example at the point of containerization (e.g., steel bars or coils, cans of paint, cylinders of gas, bottles of beverage, strips of tablets, etc.). (F Abdullah & Rajgopal, 2003; D. Dennis & J. Meredith, 2000, p. 1088) The Institute of Operations Management (IOM) identifies pharmaceuticals, cosmetics and confectionery as examples of these hybrid-manufacturing environments containing both process and discrete phases. (Lyons et al., 2013, p. 481)

When both hybridity aspects are present at the process of producing an item, these industries can be defined as semi-process industries.
In semi-process industries the continuous operation typically heads the discrete operation. This involves the conversion of natural resources or raw materials into useful components. Usually, the discrete operation takes place later in the sequence where shaping, assembling, finishing and packing operations are performed (Abdulmalek et al., 2006, p. 21; Cleland & Bidanda, 1990, p. 241)

2.4.2 Discretization point concept

At some point during the course of production in many process-manufacturing environments, the final product becomes discrete. This co-existence was highlighted by Billesbach (1994) and afterwards by Abdulmalek et al. (2006, p. 21).
The point where process production turns into discrete production was first introduced by Abdulmalek et al. (2006, p. 21) as discretization point (DP) and later used by Pool et al. (2011) to highlight this hybridity and use the term of semi-process industries.
At the discretization point the physical attribute of the products, this is referred to as the object type, changes from continuous to discrete. (Abdulmalek et al., 2006, p. 21) This aspect is crucial since it affects the types of production processes, which are the basis for definition of product industries i.e. mixing, separating, forming and chemical reactions. In other words, these processes are usually performed on continuous objects (Noroozi & Wikner, 2014, p. 1)
Due to the changing environment of this point of the process there is a high material movement coming from the operations related with the discretization of the product. This implies big storage levels and large distributions of products. Thus the main objective for most industries is to improve quality and reliability at this point, timeliness and work standardization. (Fransoo & Rutten, 1993)

Concerning the manufacturing processes that take place at semi-process industries both process and discrete manufacturing processes can be found in most industries due to the containerization of the items. Before the DP characteristics from the process industries are found and after that point, discrete industries characteristic are found.
The location of the discretization point influences the characterization of this kind of industries. How far into a transformation process a product becomes discrete can vary widely. Fawaz Abdullah (2003, p. 56) developed a general taxonomy to classify different process industries on an "*early*", "*middle*", or "*late*" scale in their manufacturing process to describe when their non-discrete units eventually become discrete.

- *Early:* An example can be the textile industry where non-discrete units become discrete relatively early in the manufacturing process.
- *Middle:* Process industries that have their non-discrete units become discrete approximately during the middle of the process; an example is the steel industry.
- *Late:* There are process industries where products become discrete at the point of containerization or during the last process just prior to the point of containerization. An example is the sugar industry or the paint industry.

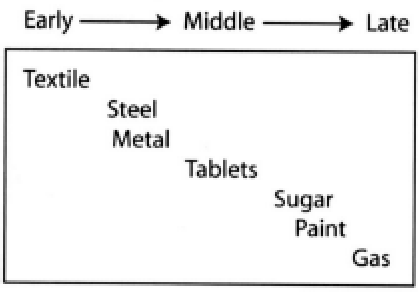

Figure 5: Classification of process industries by DP (Abdulmalek et al., 2006)

Some industries can have more than one discretization point during their manufacturing process. Therefore, the notion of the DP of this thesis will be the last DP at the production process.

2.4.3 Semi-process industries environment

Semi process industries have different characteristics before or after the DP as a result of the hybridity of the production process. The flow of materials in the semi-process industries can be either batch (intermittent) or continuous (D. Dennis & J. Meredith, 2000; Fransoo & Rutten, 1993; Noroozi & Wikner, 2014, p. 3).

Process sector is found at the first stages where products are produced in a continuous flow manner. After the discretization of the product the process enters at its discrete sector where intermittent flow is found. (Abdulmalek et al., 2006; Wikner & Noroozi, 2014)
If intermittent, there is set-up and sometimes cleaning between subsequent batches. If continuous, there is no set-up time or set-ups are short enough to be neglected. At the continuous sector of semi-process industries, non-discrete parts or quantities of a product are put into huge bulk containers. On the other side, the discrete sector can undergo both batch and job-shop production where products can be produced either individually or by groups this having connected or disconnected production lines.

If the capacity of the continuous flow mode is higher than the intermittent mode, there should be a buffer between the two parts or the production process of the continuous flow part would eventually be stopped. If first, the buffer capacity and the perishability of intermediate products should be considered. If second, the start-up of the continuous processes might be very expensive and thus, it should eventually produce in batches (Pool et al., 2011)
In case the capacity of the continuous flow part is less than the intermittent part, then the intermittent processes starve meaning loss of capacity and low utilization of production processes which usually is very expensive in semi-process industries. The balance of production at two sides, the buffer/inventory levels and the start-up or set-up times/costs should be taken into account. (Noroozi & Wikner, 2014)

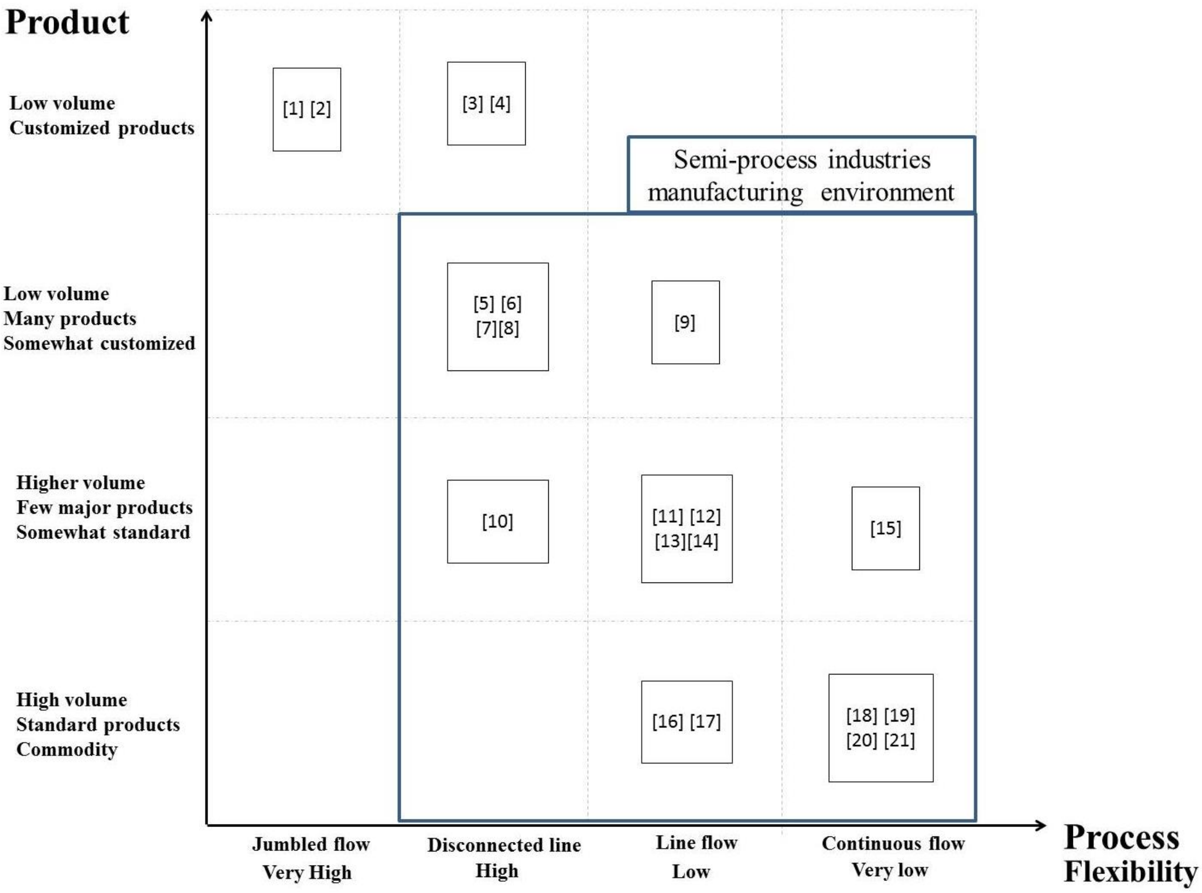

Figure 6: Product-process matrix for SPI

Figure 6 reflects where in the product-process matrix the semi-process environment is located. The production process will transfer from the continuous side of the spectrum to somewhere of the intermittent side this being separated by the discretization point.

At the continuous sector of semi-process industries products will be produced to stock. This means that stock buffers are needed at the discretisation point in order to transfer all the products from the process sector to the discrete sector. The main characteristics of continuous sectors are inflexible processes due to highly specialized dedicated equipment with long set-up times. Therefore, methodologies to improve service levels of these machines on one side, and methodologies to achieve more flexibility in the process from the other side, are a key point.

At the discrete sector of semi-process industries the products can be produced under different customer strategies. Thus, every product will have different process characteristics. Even though, one common goal is set on reducing the changeover times and producing in small batches in order to let production flow and reach low levels of WiP.

In terms of customer interaction, possibilities for semi-process industries are far fewer as the production starts at the continuous sector. At this side of the spectrum MTS policies are the most usual choices due to the inflexibility inherent at the process. On the other hand, at the discrete sector a mix between strategies can be found for different stages of the production and even for different products. Figure 7 reflects the different possibilities. Every different production strategy will be linked to a replenishment production type. MTO, ATO and MTS are all three possible interactions as products produced at the discrete sector undergo from some grade of customization to fully standard products.
Due to the discretization of the processes, semi-process industries can have hybrid customer interaction where products are produced under a MTS policy at the first sector and in function of the process typology at the discrete sector, different strategies can be picked. Thus, having any of the three analysed types. However, having a MTS product at the continuous sector and an ATO at the discrete sector will depict a lot of intermediate stock which can result in high storage costs.

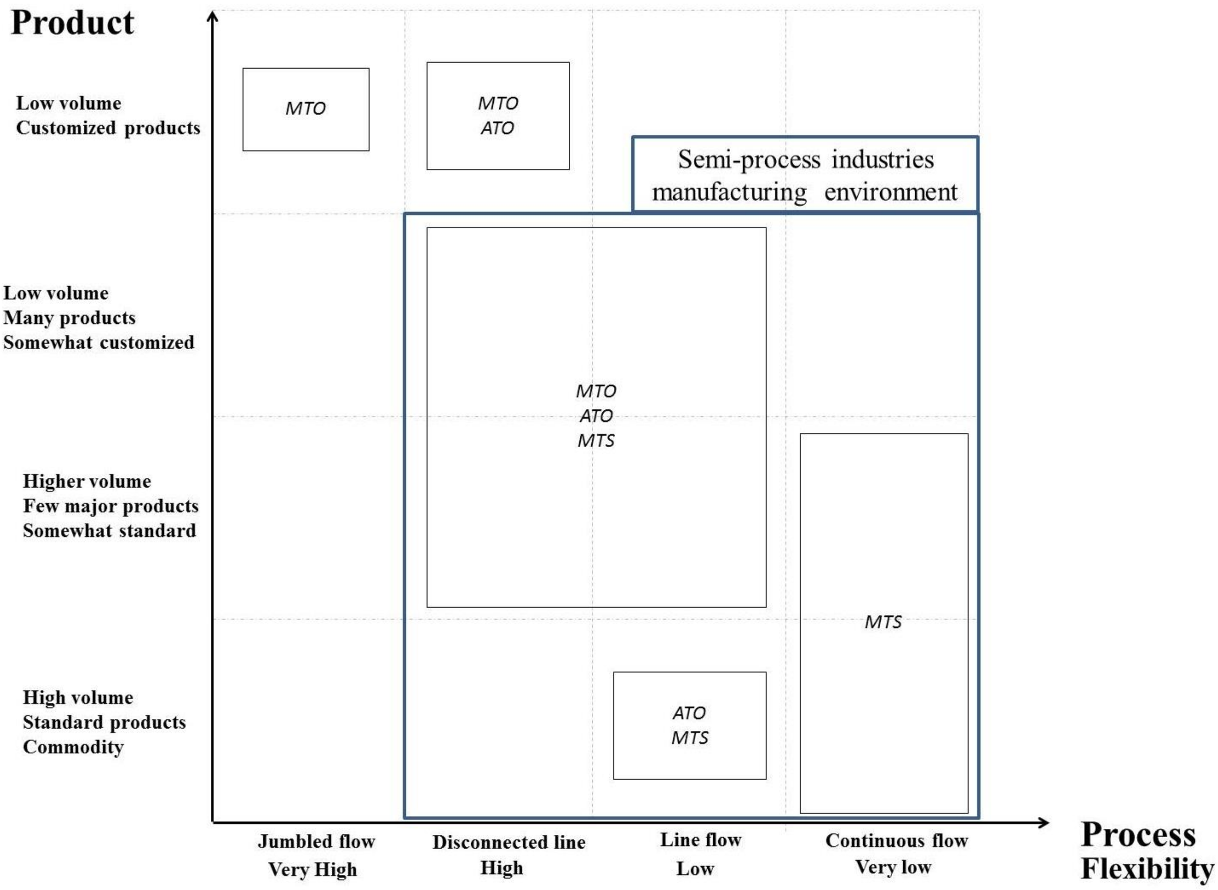

Figure 7: Product process matrix for SPI with CODP interaction

Chapter summary

Production planning and control environments are defined by the interaction of the product, process and customer. The product can be either discrete or non-discrete and it will depict the type of manufacturing process related of the industry. The process is mainly related with the plant layout and the customer interaction. This specifies the replenishment methodology used by the industry for each product.

Traditional product-process matrix developed by Hayes and Wheelwright (1979) is not only possible for manufacturing environments at the main diagonal as manufacturing environments are more flexible to adapt to new market circumstances.

Semi-process industries are identified by the hybridity inherent at the product and process. This hybridity is reflected by the discretization point. Process and discrete sector have different characteristics and thus have also different objectives in order to improve their processes.

Customer interaction for semi-process industries has different characteristics at each sector. This is closer related to the product demand than to the production process. Continuous sector normally uses MTS while discrete sector can use all three different typologies (MTS, MTO, ATO).

Chapter 3 - Lean production planning and control tools

Introduction

This chapter is focused on lean manufacturing methodologies. At the first part of the chapter a quick overview of lean manufacturing history is provided and right afterwards lean manufacturing concept is defined. Then, an analysis of the applicability at manufacturing environment done so far is provided. The main contribution of this chapter is a detailed analysis for production planning and control methodologies within lean manufacturing technics. They are defined and their applicability in manufacturing environments is characterised.

3.1 Lean history

Lean production is to a large extent based on the manufacturing principles and work processes developed by Toyota in the 1940s called the Toyota Production System (TPS) Which itself evolved from Ohno's (1988) experiments and initiatives over three decades at Toyota motor company. (Saleeshya et al., 2012, p. 20)
After World War II, Japanese manufacturers were faced with vast shortages of materials, financial, and human resources. These problems they faced in manufacturing were vastly different from their Western counterparts. These circumstances led to the development of newer and lower cost manufacturing practices. Early Japanese leaders such as the Toyota Motor Company's Eiji Toyoda, Taiichi Ohno and Shigeo Shingo developed a disciplined, process-focused production system now known as the "Toyota Production System" or "Lean Production". The objective of this system was to minimize the consumption of resources that added no value to a product. (Saleeshya et al., 2012, p. 20)
The adoption of these techniques created a critical competitive advantage of Toyota over its American competitors. Therefore, around the 80's decade scholars studied the implementation of lean techniques and by the 90's some western equipment-manufacturing companies completed the implementation of lean, reporting machines space, defects, cycle time and product delivery lead time improvements compared to their antique batch-based systems. (Kumar Chakrabortty & Kumar Paul, 2011, p. 11)

3.2 Lean manufacturing

According to APICS(John H. Blackstone Jr., 2013, p. 91) lean production is defined as

> *"A philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of the enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with customers. Lean producers employ teams of multi-skilled workers at all levels of the organization and use highly flexible, increasingly automated machines to produce volumes of products in potentially enormous variety. It contains a set of principles and practices to reduce cost through the relentless removal of waste and through the simplification of all manufacturing and support processes."*

A more straightforward definition is saying that lean is a system that produces what the customer wants, when they want it, with minimum waste. Its philosophy aims to shorten the time between the customer order and the product build and shipment by eliminating sources of waste. (Saleeshya et al., 2012, p. 20) Lean thinking focuses on value-added lean and consists of best practices, tools and techniques from throughout industry with the aims of reducing waste and maximizing the flow and efficiency of the overall system to achieve the ultimate customer satisfaction. (Kumar Chakrabortty & Kumar Paul, 2011, p. 11)
In lean manufacturing the identification and elimination of wastes (non-value added activities) is done through continuous improvement by conveying the product at the pull of the customer in pursuit of production. In a more basic term, more value with less work. (Kumar Chakrabortty & Kumar Paul, 2011, p. 11)
Manufacturing flexibility is very important for agility and can be improved by proper lean implementation. It means that industries build what the customer orders as soon as possible after the order and that the total lead-time is as short as possible. (Saleeshya et al., 2012, p. 20)

The main goal of lean manufacturing is the aggressive minimization of waste, called "*muda"*, to achieve maximum efficiency of resources. Essentially a "muda" is anything that the customer is not willing to pay for. See table 9 for the seven type of wastes identified by Taiichi Ohno at the Toyota Production System (Kumar Chakrabortty & Kumar Paul, 2011, p. 11; Mahapatra & Mohanty, 2007, p. 20; Saleeshya et al., 2012, p. 21)

Table 9: Seven wastes of manufacturing by Mahapatra and Mohanty (2007, p. 20)

Type of waste	Causes
Overproduction	Producing more product than needed
Inventory	Any supply in excess to produce product
Waiting	Idle operator or machine time
Motion	Movement of people or machine which does not add value
Transportation	Any material movement that does not directly support Value added operation
Defects	Making defective parts
Extra processing	Any process that does not add value to product

The elimination of waste helps to reduce cost and organize the required, value-creating production activities into an efficient system design that facilitates smooth production flow with minimal interruptions, delays and variations.

According to Womack and Jones (1996), to become a lean manufacturer requires a way of thinking that focuses on making the product flow through production without interruption, a pull system that cascades back from customer demand by replenishing what the next operation takes away at short intervals, and a culture in which everyone is striving continuously to improve. (Saleeshya et al., 2012, p. 20) Under these characteristics, five main lean principles are postulated (Bicheno & Holweg, 2009; King, 2009, p. 8):

- *Value:* Define value from the perspective of the customer
- *Value stream*: Represent all the value-added and non-value added activities required for a company in order to facilitate elimination of waste and achieve flow.
- *Flow:* Understand the process and eliminate any obstacles that do not add value in the value stream so that products or services flow continuously from concept to delivery to the customer.
- *Pull:* Initiate work only when requested by the customer
- *Perfection:* Continuously eliminate all waste along the process to improve in efficiency, cycle times, costs, quality and achieve continuous flow.

In order to accomplish all these principles different lean tools are proposed. Between all the related literatures found, different classifications of lean tools are made. Lyons et al. (2013, p. 477) made a classification to identify different application principles inside all the lean tools. Therefore, four wide ambitions were identified and found suitable to characterize the principles applications of lean thinking (see figure 8):

- Alignment of production with demand
- Elimination of waste
- Integration Suppliers
- Creative involvement of the workforce in process improvement activities.

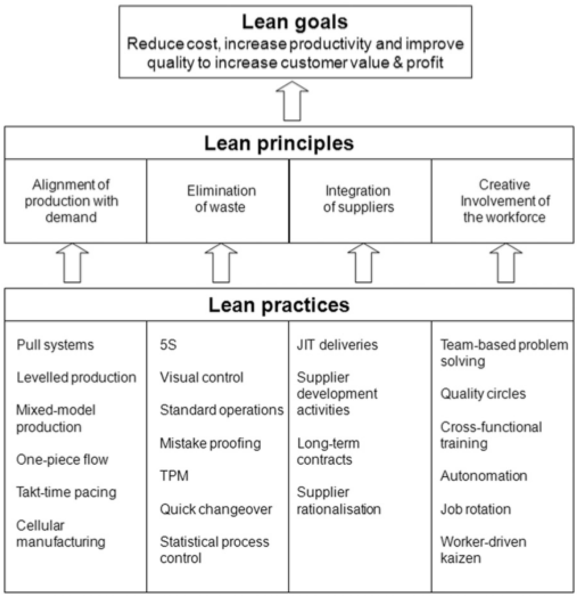

Figure 8: Outline of lean thinking framework by Lyons et al. (2013)

The second principle, the elimination of waste, is essential to facilitate the first lean principle, the alignment of production with customer demand. (Lyons et al., 2013, p. 477) This first lean principle is the lean principle for production planning and control. (Bokhorst & Slomp, 2010; Lyons et al., 2013; Powell et al., 2010) Thus, some of the tools related with the second principle are useful in order to facilitate the integration of lean PPC tools.

3.3 Application of lean in process manufacturing environments

Success in lean manufacturing has been largely associated with the discrete industry, where has demonstrated improvements in quality, cost and delivery metrics. (Powell et al., 2010, p. 243) Thus, the lean approach has been applied more frequently in discrete manufacturing than in the continuous or process sectors. (Saleeshya et al., 2012, p. 21) Possibly, because the typical characteristics of this sector. These include, as seen before, large, inflexible machines, long setup times, and the general difficulty in producing in small batches. (Kumar Chakrabortty & Kumar Paul, 2011, p. 11)

From all the lean manufacturing tools, Powell et al. (2010) and King (2009) recognize that although many of the lean tools and practices have been applied successfully in all types of industrial processes, there is a noticeable lack in the application of lean production control practices to process-type industries. However scholars such as Abdulmalek and Rajgopal (2006), Floyd (2010), King (2009), Melton (2005) and Packowski (2013) have recently studied and applied some lean PPC practices in process industries.

For example, Abdulmalek and Rajgopal (2006) present a case based approach to demonstrate how lean manufacturing practices when used appropriately, can help the process industry eliminate waste, maintain better inventory control, improve product quality, and better overall financial and operational control.

Not all the lean tools are applicable at the same manufacturing environments. Thus, when identifying which lean tools are applicable at every manufacturing environment within the process sectors, Abdulmalek et al. (2006) and Powell et al. (2010) agree on saying that there are some lean methodologies that are universally applicable to all types of manufacturing environments in the process sector, independent of its specific characteristics. These tools offer the potential for significant gains with relatively low investments as they require simple application. These tools and practices are: 5S, value stream mapping (VSM), standardization of work (SW), visual systems (VS) and Kaizen activities.

3.4 Lean PPC tools and techniques in process industries

Lean production planning and control tools are analysed in the next section for the principle of the alignment of production with demand of (Lyons et al., 2013).
Before going into detail, it is important to highlight the different names and concepts found at the literature to refer to the same lean manufacturing tools and methodologies.

- Pull systems are also refereed as Just-in-time production systems. These are replenishment control methodologies that allow production to be done based on actual customer demand. Kanban pull production is a specific approach of these systems.
- Levelled production is also known as production smoothing, or "Heijunka" in Japanese. The objective is to balance production volume as well as production mix.
  In order to level production different lean planning methodologies can be distinguished. Cyclic planning methods are repeated methodologies of planning that aims to mitigate the volume variation in demand with optimized sequences of production runs, while levelling production. Heijunka is the root lean tool from where all the other planning tools have evolved. Tools as Every-Product-Every (EPE) and product wheels are lean cyclic planning tools evolved from Heijunka concept.
- Takt time is the basic rate of production, also referred to as the drumbeat for the process of production.
- Cellular manufacturing is a model for workplace design, and is an integral part of lean manufacturing systems.

Due to the dependency of PPC lean tools with the elimination of waste (Lyons et al., 2013, p. 477), two more tools are analysed in order to help semi-process industries to reduce waste applying lean PPC tools.

- Total productive maintenance (TPM) is a tool that is necessary to account for sudden machine breakdowns.
- Quick changeovers or single minute exchange of dies (SMED) is a tool used to reduce the changeover times.

Table 10: Lean tools analyzed

Lean PPC tools	
Pull systems - Kanban pull production	
Leveled production Cyclic planning	Heijunka EPE, Cyclic wheels
Takt-time	
Cellular manufacturing	
Lean elimination of waste tools	
Total productive maintenance (TPM)	
Quick changeovers - SMED	

At process industries these lean tools have been lately applied and studied by different scholars. Table 11 summarizes the tools applied or proposed for all them. This distinction must be remarked as not all of these scholars have applied the tools but only proposed them to be applied at process industries.

Table 11: lean PPC tools applied in process Industries

Tool	**Source**	
Cellular manufacturing	Fahmi and Abdelwahab (2012) King (2009) Mahapatra and Mohanty (2007)	
Cyclic planning (EPE, cyclic wheels)	Floyd (2010) King (2009) Lyons et al. (2013) Mahapatra and Mohanty (2007)	Packowski (2013) Pool et al. (2011) Powell et al. (2010)
Heijunka	Fahmi and Abdelwahab (2012) Lyons et al. (2013)	
Kanban pull production	Mahapatra and Mohanty (2007) Melton (2005) Packowski (2013)	
SMED	Abdulmalek et al. (2006) Floyd (2010) King (2009)	Lyons et al. (2013) Mahapatra and Mohanty (2007)
TPM	Abdulmalek et al. (2006) King (2009)	Lyons et al. (2013) Mahapatra and Mohanty (2007)
Takt time	Abdulmalek et al. (2006) King (2009) Packowski (2013)	

Lean PPC tools

1- Pull systems

The lean literature offers some confusing, and often conflicting, definitions of the different production control strategies; pull and push systems (King, 2009). As a result, in this section both concepts will be defined in order as not to have a misunderstanding concept when making references to this concepts.

Push and pull concepts can refer to three different aspects; production, material control, and distribution. In this line, lean methodologies refer to production concepts. Thus APICS (John H. Blackstone Jr., 2013, p. 142) defines push system as

"In production, the production of items at times required by a given schedule planned in advance."

Moreover, APICS (John H. Blackstone Jr., 2013, p. 141) defines pull systems as

"In production, the production of items only as demanded for use or to replace those taken for use."

Thus, "*Push-type"* production control strategies are based on forecasted customer demands and aim to: (Geraghty & Heavey, 2005, p. 436)

- Maximize the throughput of the system so as to minimize shortage in supply by saturating the production (Crama et al., 2001)
- Tend to result in excess work-in-progress inventory (WIP) that hides defects in the system.
- An example in order to push production is a MRP system.

Whereas "*Pull-type"* production control strategies, pull products through the system based on actual customer demands at the end of the line. (Geraghty & Heavey, 2005, p. 436) In line with Packowski (2013) , Bokhorst and Slomp (2010) and Geraghty and Heavey (2005, p. 436) such strategies tend to:

- Reduce required planning efforts
- Shorten lead times
- Improve allocation of available products capacity
- Decrease overall inventory levels due to flexibility to react to actual consumption
- Minimize the amount of WIP that can be in a system.
- Discovers defects in the system at the risk of failure to satisfy demand.
- Examples of lean tools to pull systems are Kanban cards.

In the lean manufacturing terminology, pull systems are also called just-in-time (JIT) systems based on the lean principle of the alignment of production with demand (Lyons et al., 2013), where production only will be produced when the customer "pulls" with a customer order. (King, 2009, p. 15)

The lean literature mainly refers pull systems to the replenishment of production. But it can refer to both production and replenishment methodologies. The problem comes when defining

which customer interaction strategy is either pull or push. For example, some scholars imply that a make-to-order strategy is inherent pull, while others state that it is inherently push.
Most references seem to agree that pull includes replenishment modes where production is allowed whenever materials has been consumed, or "pulled", from a downstream inventory, and that the need of replace this pulled material is conveyed by some visual, real-time means. However, there is not a universal agreement on situations where production is allowed, not to replace consumed material, but to respond to a signal that a customer or downstream operation needs material immediately.
One reason for the lack of consistent definitions is that Taiichi Ohno, when defining the TPS, did not explicitly define pull. He describes it in a way that supports the replenishment-only school of thoughts:

"Manufacturers and workplaces can no longer base production desktop planning alone and then distribute, or push, them onto the market. It has become a matter of course for customers, or users, each with a different value system to stand in the frontline of the marketplace, and so to speak, pull the goods they need, in the amount and in the time they need them."

A suggested definition of pull by King (2009) is:

"A system that produces to replenish material that has been consumed, or material for which there are firm orders needing to be filled immediately, and in which flow is managed and synchronized by current conditions in the operation."

By that definition, MTO can be either pull or push (King, 2009; Packowski, 2013) , if flow and inventories are not managed in a way that limits WIP build-up. In the same way, MTS can be push or pull, depending on how inventories are managed. If current production is based on forecast, it is almost always push. If current production is based on current conditions on the plant floor, it is most likely pull. (King, 2009)

Lean stock replenishment methodologies are based on pull production strategies thus being real consumption the one that triggers the actual replenishment.
In this context scholars as King (2009) and Packowski (2013) distinguish different pull replenishment methodologies on the basis of MTO or MTS policies.

MTO replenishment mode:

The customer order serves directly as a replenishment signal. No inventory is needed to be hold (King, 2009) because orders are not produced on stock in advance but only when required by the customer. (Packowski, 2013, p. 145)

This methodology is especially used if inventory holding costs are high, shelf lives are short, demand is sporadic and products are characterized by a high degree of diversification or customization. The drawbacks of their applicability are that production must be adhered to customer lead time expectations and sufficient capacity buffer of production is needed. (Packowski, 2013, p. 145)

MTS replenishment modes:

For MTS products, inventory levels of products will be required. For these products, there must be inventory downstream, either as WIP or as finished product, to satisfy needs for that material during the period when other products are being produced. (King, 2009, p. 222)

In order to have the stock triggered by the actual consumption of the customer and hence, following the lean concept of “pull”, MTS replenishment modes need a signalling methodology. The most common is a re-order point (ROP) methodology.

The re-order point is a tool used to control the inventory level of each item. This inventory is monitored constantly and whenever it drops below the reorder point, a production order of a predetermined quantity is released to production. The reorder point is given by a defined safety stock level plus expected demand during lead time. (Spenhoff, Semini, Alfnes, & Strandhagen, 2013, p. 213)

Different replenishment methodologies under this concept have been found (King, 2009; Packowski, 2013): fixed or variable interval, with fixed or variable quantities.

Fixed interval methodologies have a replenishment order fixed by a stabled period of time whereas variable interval methodologies use the ROP in order to replenish the product only when the stock level drops under the ROP.

ROP ensures availability and it enables continuous flow of production due to available inventory. With this tool the resource utilization can be optimized. It requires consequently predictable demand and order lead times. Re-order point methods are component-oriented and primarily designed for items with independent demand. They are normally more appropriate the more standardized the product components are, the longer life cycles they have, and the more stable the demand (Jonsson & Mattsson, 2003; 2006, p. 972)
Furthermore ROP requires a buffer safety stock. In addition a predictable throughput time is required. The same applies for required inventory information ROP builds on historical demand data and forecasting models (Spenhoff et al., 2014, p. 169)
ROP is calculated as (Bicheno & Holweg, 2009, p. 153):

$$ROP = D\ x\ LT + SS$$

Equation 1: ROP calculation

Where: D = demand during lead time LT between placing an order and receiving delivery

SS = Safety stock

Applicability of pull

Pull lean control principle has mainly been applied in high-volume flow environments in which jobs move through the production system in one direction along a limited number of identifiable routings (Bokhorst & Slomp, 2010)
However, process industries are typically thought of being “push systems”. Difficulties of implementing JIT (pull) techniques in process industries are (Crama et al., 2001):

- Fixed capacity due to capital-intensive processes or resource constraints.
- Seasonality effects result in demand peaks which exceed capacity. Thus, planning is necessary to smooth production runs, contrary to the underlying philosophy of pull systems.

Kanban pull production

Kanban is the Japanese word for "signboard". This is the classic 'visual' signalling device (Bicheno & Holweg, 2009, p. 149) for shop floor pull replenishment control.
Kanban is a re-order point methodology (Jonsson & Mattsson, 2006, p. 972) This means, that each supplying work centre does not make anything until the next work centre requests supply. Kanban is typically the card that authorizes production of a certain product. (Powell et al., 2010, p. 245)
The number of Kanban cards is calculated using the ROP measure divided to the container or stillage quantity Q (Bicheno & Holweg, 2009, p. 153)

$$N = \frac{D \ x \ LT + SS}{Q}$$

Equation 2: Number of Kanban cards

The Kanban card operates between each pair of workstations. Although there may be several single-card Kanbans in a loop between a pair of workstations, each Kanban is the authorization both to make a part or container of parts and to move it to a specified location. (Bicheno & Holweg, 2009, p. 149) When a product has been consumed from the finished goods inventory (or supermarket), a Kanban card is passed upstream (normally placed in the Heijunka box) to allow for replenishment of the product. (Powell et al., 2010, p. 245) Consequently, Kanban avoids overproduction (Spenhoff et al., 2014, p. 170) This being a design solution to materials flow problems within a process.

An enhancement of the Kanban approach is constant work-in-process (ConWIP). The basic idea is similar but ConWIP takes into account not only one, but several production steps. In this way, the various production steps work together instead of individually. By applying this methodology the total amount of Kanbans can be reduced which means less WiP. (Geraghty & Heavey, 2005, p. 436; Packowski, 2013, p. 153)

Applicability of Kanban

- Kanban is a method that works best with a regular and stable demand (Bicheno & Holweg, 2009, p. 149) (Flavio & Moacir, 2011) (Jonsson & Mattsson, 2006, p. 972) where the products have a simple and flat bill of material and short lead times together with small order quantities (low volume demand). (Jonsson & Mattsson, 2006, p. 972)
- Kanban is best suited in stable environments and plants involved in discrete repetitive production, i.e. assembly operations with stable demand. (Bicheno & Holweg, 2009, p. 149; Powell et al., 2010, p. 243) (Flavio & Moacir, 2011) Between the different production layouts, it suits better at flow-shop layouts with sequence

independency.(Flavio & Moacir, 2011)

- Low setup and changeover times are required to apply Kanban (Flavio & Moacir, 2011) (Spenhoff et al., 2014, p. 170), if having long changeover times application of SMED can be useful (Spenhoff et al., 2014, p. 170)
- Powell et al. (2010, p. 245) argues that the application of Kanban is considered unsuitable in process-type industries. This is because, in process-type industries, large investments are made in even larger machines, often involving long changeover and setup times. With such large change-over times, introducing Kanban would have detrimental effects to the responsiveness of the production system, and may drastically increase production lead-times. Nevertheless, King (2009) and Packowski (2013) propose Kanban signalling methods in order to communicate the need to produce material to replenish material pulled from a SKU for non-repetitive environments in process industries for low volume high variability demand products.
- Kanban is best suited for high volume, repetitive production of a low variety of highly standardized products. (Powell et al., 2010, p. 243) (Flavio & Moacir, 2011)
- Olhager and Wikner (2000, p. 217) states that Kanban fits better for items made to stock with rate based demand

2- *Takt-time pacing*

A tool used to standardize work is what is called "takt" time. Takt is the German word for rhythm or beat. Thus, takt-time refers to how often a part should be produced in a product family based on the actual customer demand. The target is to produce at a pace not higher than the takt time.
Takt time is calculated based on the following formula (Fawaz Abdullah, 2003, p. 19; Mahapatra & Mohanty, 2007, p. 21)

$$Takt\ time = \frac{Available\ work\ time\ per\ day}{Customer\ demand\ per\ day}$$

Equation 3: Takt time calculation

Takt time is the basic rate of production, also referred to as the drumbeat for the process of production. Takt time uses the language of supply and demand, where it attempt to allow for the supply to meet or even exceed the demand in order to ensure that the customer order is fulfilled and avoid disappointment. Takt time is usually calculated prior to generating a schedule, the rest of the operations have to be aligned with the Takt time in order to avoid delays or shortages. However, instances where a production facility is faced with uncertainties such as the arrival of urgent orders, unpredictable machine breakdown or resource shortages may have an impact on the Takt time calculated. In such cases the Takt time needs to be recalculated incorporating remedial actions in order to redo the schedule. (Mahapatra & Mohanty, 2007, p. 21)

Applicability

- Takt time lean control principle has mainly been applied in high-volume flow environments in which jobs move through the production system in one direction along a limited number of identifiable routings (Bokhorst & Slomp, 2010)
- It is better applied in stable and standardized production.

3- *Cellular manufacturing:*

Cellular Manufacturing is a model for workplace design, and is one of the cornerstones when applying Lean Manufacturing. (Fawaz Abdullah, 2003, p. 10; Kumar Chakrabortty & Kumar Paul, 2011, p. 12)
Cellular manufacturing, sometimes called cellular or cell production, arranges factory floor labour into semi-autonomous and multi-skilled teams, or work cells, which manufacture complete products or complex components. (Kumar Chakrabortty & Kumar Paul, 2011, p. 12) Families of parts are produced on one line or in one cell. (Abdulmalek et al., 2006, p. 16) This means organizing the entire process for a particular product or similar products into a group (or ‘‘cell’’), including all the necessary machines, equipment and operators. Resources within cells are arranged to easily facilitate all operations. (Abdulmalek & Rajgopal, 2006, p. 224) A cell consists of equipment and workstations that are arranged in an order that maintains a smooth flow of materials and components through the process. (Fawaz Abdullah, 2003, p. 10)

Cellular manufacturing increases the mix of products with the minimum waste possible. (Fawaz Abdullah, 2003, p. 10) Properly trained and implemented cells are more flexible and responsive than the traditional mass-production line, and can manage processes, defects, scheduling, equipment maintenance, and other manufacturing issues more efficiently. (Kumar Chakrabortty & Kumar Paul, 2011, p. 12)
The first step in designing cellular manufacturing systems is to define the functional requirements of the system at the highest level of its hierarchy in the functional domain. (Kumar Chakrabortty & Kumar Paul, 2011, p. 12)

Arranging people and equipment into cells has great advantage in terms of achieving lean goals. One of the advantages of cells is the one-piece flow concept, which states that each product moves through the process one unit at a time without sudden interruption, at a pace determined by the customer’s need. (Fawaz Abdullah, 2003, p. 10; Kumar Chakrabortty & Kumar Paul, 2011, p. 12)

Extending the product mix is another advantage of cellular manufacturing. When customers demand a high variety of products as well as a faster delivery rates, it is important to have flexibility in the process to accommodate their needs. This flexibility can be achieved through grouping similar products into families that can be processed on the same equipment in the same sequence. This will also shorten the time required for changeover between products, which will encourage production in smaller lots. (Fawaz Abdullah, 2003, p. 10)

Other benefits highlighted by Fawaz Abdullah (2003, p. 10) and King (2009, p. 195)associated with cellular manufacturing include:

- Inventory (especially WIP) reduction
- Reduced transport and material handling
- Better space utilization
- Lead time reduction
- Identification of causes of defects and machine problems
- Easier implementation of pull replenishment systems
- Improved productivity
- Enhanced teamwork and communication
- Enhanced flexibility and visibility

Applicability

- Environments with high equipment flexibility, where equipment is arranged in functional layout were one machine can process many product types. (Abdulmalek et al., 2006, p. 22)
- It is applicable in job-shop production layouts in industries with parallel, dedicated equipment. For example, a chemical industry can take benefit from this tool. (Abdulmalek et al., 2006, p. 22)

4- *Cyclic planning*

Cyclic planning are planning methodologies that are able to handle different batch sizes and product mix. These are repeated methodologies of planning that aim to mitigate the volume variation in demand with optimized sequences of production runs. One key element for cyclic planning is the equipment flexibility as it creates flow line with temporary dedicated machines, (Spenhoff et al., 2014)
For intermittent flow companies, cyclic planning methods have been suggests as an effective way to deal with the fill rates, the inventory levels and the utilization of equipment. (Noroozi & Wikner, 2014)
A high product variety is often associated with small lot sizes where reducing the setup time becomes a key issue. When capacity is fully utilized, the emphasis is on the setup costs in the process industry, where setup times are often very long (e.g. for cleaning processes) and, due to high capital investment costs, any downtime is very expensive.

Cyclic planning methods in the process industry, plan for a setup optimized sequence of batches of different product variants. Capacity that is not fully utilized is often maintained for strategic reasons, such as short waiting times and therefore short lead times, especially when customer tolerance times are short and the emphasis is on reducing the setup time.

Applicability

- Cyclic planning has demonstrated its efficiency in batch process industries with high volume, low value products (J. Ashayeri, Heuts, Lansdaal, & Strijbosch, 2006)

- In general, cyclic planning methodologies (such as EPE), are applicable in many environments and that the benefits range from shorter production lead-times and lower work-in-process inventories and safety stocks, to improved material handling and material flow and increased customer responsiveness. (Powell et al., 2010, p. 245)
- Cyclic schedules have proven to be an effective method to synchronize subsequent non-discrete production stages (Glenday, 2006; King, 2009). The repetition of cyclic schedules offers advantages both for shop floor activities and for planning. It may help to detect disturbances earlier and reduce set up time and costs. It creates continuous improvement activities evolving workers at the methodology. Cyclic schedules also enhance chain coordination, as planners and operators as well as suppliers and customers get acquainted to the fixed schedule. In turn this saves time for coordination and enables an anticipatory attitude. (Pool et al., 2011, p. 195)

Evolution of cyclic planning methodologies

Levelling production as constant as possible from day to day is the lean concept for production smoothing, Heijunka in Japanese. Scholars have recently evolved this planning system to repetitive production planning methods, which are being applied at process industries. Evolving from the Heijunka lean tool four different planning methodologies have been found. The Every Product Every interval (EPE) planning concept, which has been applied by scholars as Powell et al. (2010), enhances the repetitive planning concept. The Cyclic Wheel planning concept from King (2009) introduces the "*product wheel*" or cyclic wheel planning concept. Derived from King, Floyd (2010) applied what he calles the "*Fixed Sequence Variable Volume*" (FSVV) planning methodology, which is similar to King's product wheel. Lately Packowski (2013) introduced the "*Rhythm Breathing wheel*" concepts adding new parameters to deal with high mix of different product portfolios.

All these methodologies are analysed at the next section.

Figure 9: Different product wheel from Packowski (2013)

Levelled production or Heijunka

Production leveling also referred to as production smoothing or Heijunka in Japanese is an essential element of the Toyota Production System and lean production, respectively. (King, 2009)

The objective of Heijunka is to balance production volume as well as production mix by decoupling the production orders of customer demand. Hereby, production leveling decreases variation in form of peaks and valleys in the production schedule balancing the work load in production and logistic processes. (Powell et al., 2010, p. 245) It permits companies to enhance efficiency by reducing waste, overburden of people or equipment, and uncertainty.

It enables high level of schedule visibility generating a cyclic and constant production mix (Powell et al., 2010, p. 243) and assuming that changeover times are negligible. (Pool et al., 2011) Hence, any sequence of products can be produced at any given time (Powell et al., 2010, p. 245)
Under Heijunka methodology, production is scheduled such that the production line produces the same sequence of products throughout a given time period, with that sequence alternating between demanding and less demanding products. (Hüttmeir, de Treville, van Ackere, Monnier, & Prenninger, 2009, p. 501) (Powell et al., 2010, p. 245; Wilson, 2014, p. 4)

Conventional leveling approaches aim at distributing production volume and mix to equable short periods. The sequence of these periods describes a kind of manufacturing frequency. According to this leveling pattern every product type is manufactured within a periodic interval, for example a day or a shift. The duration of this interval is depicted by the key figure EPEI (every part every interval). The EPEI-value is used as an index for reactivity and it also reflects lot sizes. An EPEI-value of one day, for example, reveals that all product types are manufactured once a day.(Bohnen, Buhl, & Deuse, 2013)

Bicheno and Holweg (2009) suggests that Heijunka is a post box system for Kanban cards that authorizes production in pitch increment- sized time slots. A typical pitch increment is between 10 and 30 minutes.

Heijunka aims at reaching a higher average resource utilization and smoothing the resource utilization (Powell et al., 2010, p. 243). Producing under a Heijunka plan does not follow a given sequence of order, but batch orders of a specific period of time. Further, production of the various products in the company's product mix is achieved via the production of small quantities, as opposed to large lots. (Spenhoff et al., 2014; Wilson, 2014, p. 4)

Applicability

- Heijunka typically requires limited product diversity combined with stable and predictable customer demand. Due to that, the application of conventional leveling approaches (i.e. manufacturing every product type within a periodic interval) is limited to large scale production. Nevertheless, Heijunka can also be implemented in low volume and high mix production (Bohnen et al., 2013)
- Heijunka as well as Kanban, has mostly been applied in discrete, repetitive, assembly-type production. (Powell et al., 2010, p. 243) Thus, high set-up and changeover times will not fit for Heijunka.
- Heijunka is more appropriate for high volume, repetitive production of a low variety of highly standardized products. (Powell et al., 2010, p. 243) As product variety increases, however, the practice of Heijunka becomes more challenging**.** (Hüttmeir et al., 2009, p. 501)

According to Bicheno and Holweg (2009, p. 161) Heijunka should be regarded as the final Lean tool because so much must be in place for it to be a real success – cell design, mixed model, low defects level, Kanban loops and discipline, changeover reduction, and operator flexibility and authority. That is the ultimate tool for stability, productivity and quality.

EPE

The EPE concept comes from the lean movement of the 1990s and is an evolution of Heijunka, based on cyclic planning. The main aim is to increase the predictability of the planning strategy introducing a fixed plan, and then reduce gradually the batch sizes towards the one-piece flow concept.(Fauske, Alfnes, & Semini, 2008, p. 4)
Powell et al. (2010, p. 245) propose the following definition for EPE:

> *"EPE is a lean production control method that involves creating a fixed cyclic plan through the levelling of product volume and mix, with a continuous focus on setup reduction."*

EPE is based Heijunka, where product sequence and product volume are fixed. The basis of EPE is to make each cycle of the plan as small as possible by doing as many changeovers as feasible, in keeping with lean principles. (Powell et al., 2010, p. 245)
This characteristic contrast with Heijunka, where changeover times are assumed to be negligible. Therefore products neither have sequence nor volume restrictions. As a result, EPE concept is more applicable to process-type industries than Heijunka and Kanban as the length of an EPE cycle can be chosen for convenience, and may be a day, a week or longer.

Powell et al. (2010, p. 245) suggest that a fixed EPE plan will also deliver greater stability and predictability to the production environment, which results in less planning effort and simplified coordination across the value-stream. Consequently, more time can be spent on improvement efforts, such as setup reduction.

The main goal of mixed-model production practices is to build every model, every day, according to daily demand. (Olhager & Wikner, 2000, p. 216) The mixed-model production aims to schedule products in a repeating sequence rather than in large batches. (Bicheno & Holweg, 2009, p. 146) Thus an ABC, ABC, ABC sequence would be used instead of three large batches. According to Bicheno and Holweg (2009, p. 146) The main reasons to apply mixed-model scheduling are:

- It is a powerful aid to cell balancing (by placing long cycle items next to short cycle items)
- It reduces WIP inventory and sometimes finished goods inventory
- It may lead to better customer service
- It results in a constant rate of flow of parts to the line or cell by material handling, rather than at different rates for different products.

Cyclic planning methodologies such as every product every interval (EPE) are influenced by the degree of mixed model scheduling. This depends itself upon order sizing, shipment frequency and changeover. Thus, there is a need to decide the period for repeating mixed model sequence. In non-changeover or short operations mixed-model production should fit. (Bicheno & Holweg, 2009, p. 146)

Product wheels

Product wheels have also evolved from Heijunka, and are therefore a modified version of the production scheduling tool. This tool is defined by King (2009, p. 206) as:

"A visual metaphor for a structured, regularly repeating sequence of the production of all the materials to be made on a specific piece of equipment, within a reaction vessel, or within a process system."

Product wheels can be applied at a machine when flow is not continuous or even well synchronized and each step of the production process is separated by the others with in-process inventory. Or it can also be applied at an entire line when the production line has continuous flow. Therefore, candidates for a product wheel application include any step in the process, individual piece of equipment, or any entire production line that has appreciable changeover times or losses. (King & King, 2013) "Appreciable" in this context means any changeover over long enough or experiencing enough material loss that It affects the scheduling of the step. (King, 2009 p.211)
Product wheels follow pull replenishment principles, where production is based on actual consumption rather than in forecast predictions. Products are scheduled in order to reduce changeover and minimize cycle times. Every product has a position assigned at the designed wheel. However, not all the products are produced every cycle. High-volume demand products are thought to be produced every cycle whereas the lower-volume products are scheduled to be produced on a frequency less than every cycle.

A visual representation of the product wheel approach is provided in Figure 1. (Wilson, 2014)

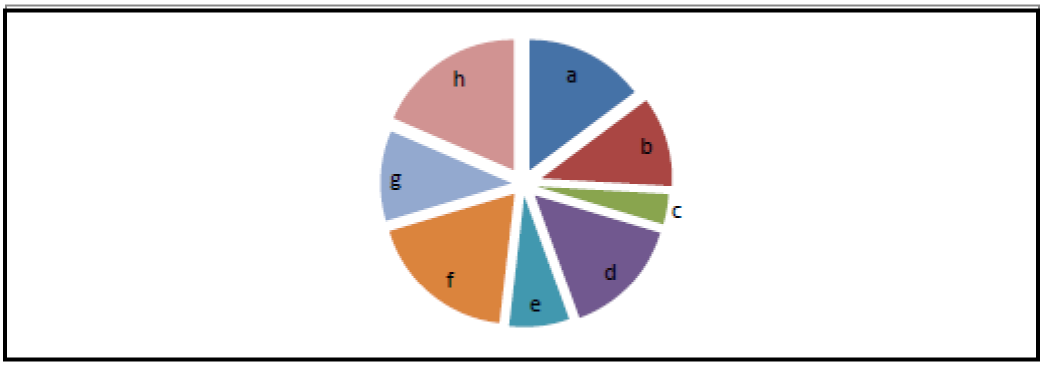

Figure 10: The Product Wheel Approach adapted King (2009) in Wilson (2014)

Benefits from product wheels:

- Tend to level production as a natural behaviour
- Optimize production sequence
- Add structure and predictability to high-variety operations
- Provide a basis for informed decision about production sequence and campaign length
- Provide a basis for informed decisions about MTO and FTO for appropriate products
- Optimize transition cost versus inventory carrying cost
- Provide a structured basis for determining cycle stock requirements

- Provide a structure basis for calculating safety stock requirements
- Quantify the benefits available for further SMED activity

FSVV

In *Liquid Lean*, Floyd (2010) describes a production scheduling technique called "*fixed-sequence variable volume*" (FSVV), which is very similar to the product wheel methodology of King (2009). As its name implies, finding the optimum sequence to minimize changeover time and cost is of big importance, just as it is with wheels. Like wheels, FSVV follows pull replenishment principles, where what is produced during any campaign is based on actual consumption rather than on any predetermined amount. And like wheels, it produces the lower-volume products on a frequency less than every cycle.

The key difference is that rather than setting a fixed wheel time, FSVV allows total cycle time to float. The primary reason is that it has been applied at capacity limit environments. Therefore, with high demand and difficult changeovers, operations tend to run long cycles. The key to shortening the cycle time is reducing changeover time by finding a better sequence, but determining the optimum sequence is very difficult, and is therefore a focus of continuous improvement activities. Incremental sequence improvements are being made regularly, so effective capacity is almost continuously increasing while cycle time is almost continuously decreasing. (King & King, 2013)

Although overall cycle time is allowed to float, it is consistent enough from cycle to cycle that cycle stock requirements can be determined reasonably well. Cycle stock is calculated on two different ways. The first one referred to days of demand in inventory and the second one distinguishing importance of products with the ABC importance classification.

Rhythm wheels

In *LEAN Supply Chain Planning*, Packowski (2013) proposes a cyclic planning concept based on the product wheel from King (2009) but dealing with high-mix variability environments. He proposes a methodology to apply cyclic planning to all the environments depicted by the ABC-XYS product differentiation. Production is synchronized all along the supply chain below a common 'takt' in order to mitigate waste of time between production steps.

As King (2009) and Floyd (2010) did before Packowski (2013) proposes the application of three different product wheels depending on the product portfolio. The first one, called *"Classic rhythm wheel"* is exactly the same product wheel from King. With fixed sequence and fixed production quantities. The second one, called *"Breathing rhythm wheel"* varies where cycle times can vary depending on the demand of each cycle. The third wheel type he introduces is the same concept introduced by Floyd. The *"High-mix rhythm wheel"* pretends to deal with high-mix variability product portfolios having variable sequence and variable cycle times on each wheel. This is done buffering the variability with different safety stock for each possible demand variation.

Packowski (2013) main contribution comes with the applicability of what he calls *"Factoring methodologies".* This is a systematic approach to be able to deal with non-expected variation on cycle times. Applying boundaries at the rhythm wheels leads to have a close control of the process. Whenever a demand variation appears, a factoring methodology should be applied in order cope the problem without losing production efficiency.

Moreover, Packowski (2013) explains how to link scheduling methodologies with replenishment methodologies. There is not any new concept introduced as the "*Inventory Replenishment Level"* methodology proposed is not more than an approach of a fixed quantity replenishment methodology and the "*Buffer Management"* methodology is no more than an application of the ROP replenishment concept, fixed quantity. Nonetheless, the methodology explained is really detailed and provides an easy and visual understanding of all these concepts.

To sum up this section, table 12 reviews the different properties of the lean planning methodologies found.

Table 12: Lean cyclic planning methodologies

	Heijunka	**EPE**	**Product Wheel**	**FSVV**	**Rhythm Wheel**		
					Classic RW	**Breathing RW**	**High-mix RW**
Product segmentation	Product volume	Product volume Demand variability Repeaters/runners / strangers	Product variability Product demand MTO/MTS	ABCD, volume/value	Product variability Product volume Repeaters/Runners/ Strangers ABC classification		
Production mix	Fixed mix-model scheduling	Variables	Fixed mix	Fixed mix	Fixed	Fixed	Different products each cycle
Replenishment	None (MTO) Stock (MTS)-Kanban	Finished goods inventory (MTS)	None (MTO) Safety Stock (MTS) Fixed interval Fixed quantity	Days of Demand in Inventory ABC inventories	Variable quantity (IRL) Fixed quantity (Buffer Mgt.) None (MTO)		
Production sequence	To even out peaks and troughs in the quantities produced Negligible changeover times	Setup reduction Changeover times and batch reduction	Changeover difficulty	Min. high cost transitions and max. low cost transitions.	Best changeover sequence and high utilization on the bottleneck operation		
Cycle time	Fixed	Fixed	Fixed	Variable	Fixed	Variable	Variable
Production quantities	Fixed, Quantities equal to demand	Variables	Fixed	Variable	Fixed	Variable	Variable

A differentiation between all the lean cyclic planning methodologies studied will be done at this thesis. Distinguishing Heijunka on one hand, and cyclic wheels on the other.
The purpose of this differentiation is to keep using the already known Heijunka as a typical lean planning methodology, which is mainly applied at discrete industries with short-changeover times. And on the other hand, the rest of cyclic planning methodologies propose similar things that can be grouped on the cyclic wheel concept.

Thus between cyclic wheels, distinction is made between fixed or variable quantities and fixed or variable sequences. The main differences with Heijunka are their applicability at different manufacturing environments due to the sequence and quantities variations.

Finally, to apply cyclic planning methodologies properly, product differentiation has been found an important concept to take into account.

Product differentiation

A differentiation in terms of production frequency is a powerful lean scheduling concept.
Scholars use two different types of segmentations. ABC – XYZ which deals with demand variability and demand volume of products and the ABC classification which deals with demand volume and value of the products.

Table 13: Different product segmentation by authors

ABC-XYZ	ABC
Bicheno and Holweg (2009)	Bicheno and Holweg (2009)
Bohnen et al. (2013)	Floyd (2010)
Packowski (2013)	King (2009)
Powell et al. (2010)	Packowski (2013)

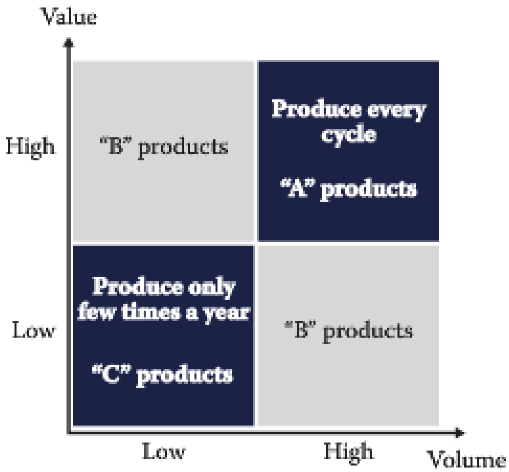

Figure 11: Volume and value product difference by Packowski (2013)

The ABC classification of products by volume and value is used by Packowski (2013) to decide which products should be produced more frequent at a high-mix variability demand environment. Floyd (2010) and Bicheno and Holweg (2009) use the classification as an inventory policy to distort the amount of material in inventory to protect the high-value products and customers. Thus, under this classification, high volume high value products should be produced every cycle in order to maintain high levels of inventory and satisfy customer expectations. Whereas, low volume low value products should be produced not every cycle taking the risk of running out of stock whenever customer order arrives.

To segment the product portfolio the ABC-XYZ classification considers both demand volume and variability. While some products are sold in high volumes for which demand is typically very stable and easy to predict, others are sold only sporadically with less predictable demand. A combination of widely spread ABC and XYZ analyses can be used to segment the product portfolio based on these two characteristics. Bicheno and Holweg (2009) introduced the idea originated during the late 1980s of dividing the products into those that have high volume, regular demand (runners), intermediate volume (repeaters) and low volume (strangers). This has become a powerful idea for lean scheduling applied for recent scholars as Powell et al. (2010, p. 245) and Packowski (2013, p. 93)

On the basis of the ABC-XYZ segmentation, distinct planning strategies can then be defined to optimally plan production and replenishment of runners, repeaters, and strangers products.

- *Strangers:* products with low demand volumes and high demand variability
- *Repeaters*: medium-demand volume with medium variability products
- *Runners***:** fast-moving products with high demand volumes and low demand variability

Note that runners, repeaters and strangers can refer to component parts or end products. (Bicheno & Holweg, 2009, p. 146)

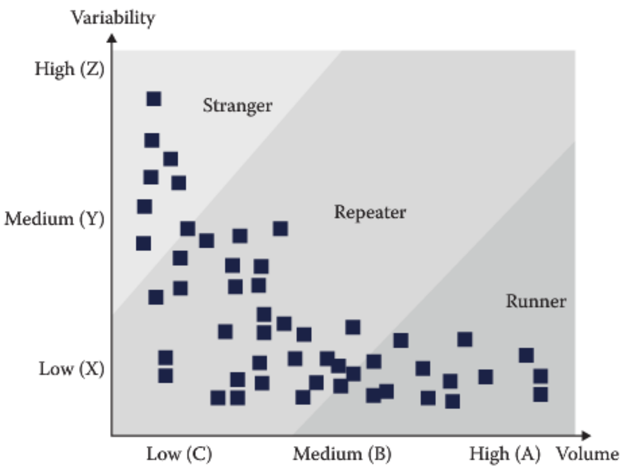

Figure 12: Segmentation of products in ABC-XYZ classification by Packowski (2013)

Other lean tools

As said before other lean tools such as TPM and SMED will help the applicability of lean PPC tools.(Lyons et al., 2013) Thus, they are analysed at this last section.

Total productive maintenance (TPM)

TPM is a waste elimination tool for machinery that consists of preventive maintenance, corrective maintenance, and maintenance prevention. (Abdulmalek et al., 2006, p. 16)
As machine breakdown is one of the most important issues that concern the people on the shop floor. The reliability of the equipment on the shop floor is very important since if one machine breaks down the entire production line could go down. An important tool that is necessary to account for sudden machine breakdowns is total productive maintenance. In almost any lean environment setting a total productive maintenance program is very important. (Mahapatra & Mohanty, 2007, p. 21)
Workers carry out regular equipment maintenance to detect any anomalies. The focus is changed from fixing breakdowns to preventing them. Since operators are the closest to the machines, they are included in maintenance and monitoring activities in order to prevent and provide warning of malfunctions.(Abdulmalek & Rajgopal, 2006, p. 224)

There are three main components of a total productive maintenance program: preventive maintenance, corrective maintenance, and maintenance prevention. (Mahapatra & Mohanty, 2007, p. 21)

- Preventive maintenance has to do with regular planned maintenance on all equipment rather than random check-ups. Workers have to carry out regular equipment maintenance to detect any anomalies as they occur. By doing so sudden machines breakdown can be prevented, which leads to improvement in the throughput of each machine.

- Corrective maintenance deals with decision such as whether to fix or buy new equipment. If a machine is always down and its components are always breaking down then it is better to replace those parts with newer ones. As a result the machine will last longer and its uptime will be higher.

- Maintenance prevention has to do with buying the right machine. If a machine is hart to maintain (e.g., hard to lubricate or bolts are hard to tighten) then workers will be reluctant to maintain the machine on a regular basis, which will result in a huge amount of lost money invested in that machine.

Applicability

- This tool is applicable in all different types of manufacturing environments. However, TPM is more important in processes where production is done under long runs and reliability of the system is important.

SMED

Ohno developed SMED in 1950 at Toyota. Ohno's idea was to develop a system that could exchange dies in a more speedy way. By the late 1950's Ohno was able to reduce the time that was required to change dies from a day to three minutes. The basic idea of SMED is to reduce the set up time on a machine. (Abdulmalek et al., 2006, p. 16; ElMaraghy et al., 2013, p. 641; Mahapatra & Mohanty, 2007, p. 21) Moreover, it involves concepts such as cycles that optimize change-over times, or re-tooling whole sets of tools for product families and careful planning of the number of tools or machines to cope with variants efficiently (ElMaraghy et al., 2013, p. 641)

There are two types of setups: internal and external.

- Internal setup activities are those that can be carried out only while the machine is stopped
- External setup activities are those that can be done while the machine is running.

The idea is to move as many activities as possible from internal to external. After all activities are identified then the next step is to try to simplify these activities (e.g., standardize setup, use fewer steps and tools). By reducing the setup time many benefit can be realized. First, change specialists are not needed. Inventory can be reduced by producing small batches and more variety of product mix can be run. Line balancing is considered a great weapon against waste, especially the wasted time of workers. The idea is to make every workstation produce the right volume of work that is sent upstream workstations without stoppage. This will guarantee that each workstation is working in a synchronized manner, neither faster nor slower than other workstations. (Fawaz Abdullah, 2003, p. 21)

Applicability

- Changeover reduction can be applied at every process having time losses between production runs. However, it is more reliable at this processes with a large number of changeovers, were a small reduction of time will have a bigger repercussion

After going into all the different lean PPC tools it can be concluded that the applicability of lean PPC tools is not straightforward and must be adapted to each case. Nonetheless, some characteristics are highlighted to try to have a generalist view. Table 14 summarizes all the different environment characteristics where these tools are applicable.

Table 14: Review of the applicability of lean PPC tools

Lean PPC tools	Applicability	Sources
Kanban pull production	Regular and stable demand Flat BOM Short lead times Low volume product demand Low changeover times Low setup times Standard products High volume, low variety of standard products. Discrete, repetitive environment Flow shop layouts with sequence independency made to stock items with rate based demand	Bicheno and Holweg (2009) Flavio and Moacir (2011) Jonsson and Mattsson (2006) King (2009) Olhager and Wikner (2000) Packowski (2013) Powell et al. (2010) Spenhoff et al. (2014)
Cellular manufacturing	High equipment flexibility Functional layout Job-shop production Parallel dedicated equipment High variety of products	Abdulmalek et al. (2006) King (2009)
Heijunka	Low changeover & set-up times Discrete, repetitive environments Stable demand High volume, standard products Low volume , high mix products Low variability demand	Bicheno and Holweg (2009) Bohnen et al. (2013) Pool et al. (2011) Powell et al. (2010) Spenhoff et al. (2014)
Takt time	Stable demand Standardized process High volume flow production environments Few different routings	Abdulmalek et al. (2006) Bokhorst and Slomp (2010) Mahapatra and Mohanty (2007)
Cyclic planning	Different batch sizes Product mix Dynamic demand Intermittent and continuous flow production Repetitive environments High volume, low value products High sequence dependency and long changeover times	J. Ashayeri et al. (2006) King (2009) Noroozi and Wikner (2014) Packowski (2013) Powell et al. (2010)

Chapter summary

Applicability of lean tools in process sectors still remains behind discrete sectors due to the rigid process characteristics (i.e. inflexible equipment, long changeover times and sequence dependency).

Lean PPC deals with the alignment of production with demand (Lyons et al., 2013) Its main tools are levelled production with cyclic wheel planning and Heijunka, pull production with tools as Kanban, takt time pacing and cellular manufacturing. The applicability of all these tools is not straightforward for all manufacturing environments as they fit better with some specific characteristics.

Other lean tools such as TPM and SMED can help the applicability of lean PPC tools as they reduce waste in other levels. These tools can be applied at any process environment. Even though, they can rich higher results in specific environments.

From all the tools studied, cyclic planning methodologies, as Heijunka and cyclic wheels, seem to be the ultimate lean tools for PPC in manufacturing environments. This is because they can be applied under different production volumes and different product variability. Moreover, the application of cyclic planning methodologies implies application of other waste reducing methodologies which help having an smoother production. (e.g. Best production sequence, changeover time reduction and product family production)

Replenishment methodologies under lean management are thought to be triggered by customer needs, with a pull system. Within this concept, two different types have been defined being either MTS or MTO. An ATO approach would represent a hybrid push/pull production which has not taken into account at this thesis as it represents a complex system with intermediate stock.

Finally it is important to remark that not only are the production environment characteristics important when applying lean PPC methodologies, but also the differentiation in terms of product value, demand volume and demand variability.

Chapter 4 – Lean PPC in Semi-process Industries

Introduction

Lean PPC tools analysed at Chapter 3 are proposed to be applied in the manufacturing environment of semi-process industries in this chapter.
First, a distinction between process and discrete sector is made. Applicability of the lean tools studied at Chapter 3 is proposed for each different objective of the production processes highlighted in Chapter 2.
Afterwards, the applicability is analysed in more detail at every different environment of semi-process industries.
Finally, it has been found interesting to analyse the applicability in terms of product demand volume and variability.

4.1 Applicability in terms of process sector

Applicability of lean methodologies at this industry type is not straightforward and it has not been documented by many scholars. Abdulmalek et al. (2006), Melton (2005) and Pool et al. (2011) have studied and implemented some lean production planning and control tools at this semi-process environments.

Lean PPC tools in Semi-process industry should be separated in the two different sectors defined by the last DP of the production. This distinction is important in order to apply properly lean tools. (Pool et al. 2011, p 202) Therefore, different tools can be applied at the process sector of semi-process industries.

Table 15: Lean tools applicable at each SPI sector

Process Sector	Discrete Sector
Cyclic wheel planning Takt time TPM	Cellular manufacturing Cyclic planning Heijunka Kanban SMED TPM

Table 15 summarizes the applicability of the lean tools studied in each sector of semi-process industries. The tools proposed have been selected in line with the Chapter 2 of the thesis.

In semi-process industries production starts with the continuous production which is produced in a continuous mass production of items. Taking back the main objectives for each production process lean tools can be selected:

- *Minimize cycle time:* To minimize cycle time cyclic planning can be beneficial as it is based in scheduling the optimum production sequence in order to reduce the changeover times between production runs of different products. This will help production to realize regularity in this continuous part of the production. (Pool et al. 2011, p.202) Moreover, producing under a common takt can reduce production spare times.

- *Maximize reliability of the system:* To maximize reliability of the system waste elimination lean tool of TPM can be applied in order to maintain high levels of service utilization on machines. (Mahapatra & Mohanty, 2007, p. 21) Moreover, cyclic planning has been suggests as an effective way to deal with the fill rates, the inventory levels and the utilization of equipment. (Noroozi & Wikner, 2014)

On the other hand, semi-process industries discrete sector will be mostly a job shop or batch shop production systems. At this sector, different manufacturing environments can be found and hence, different lean tools can be applied. Some tools are proposed to accomplish the objectives remarked. Even though, these tools proposed are not all of them.

- *Minimize set-up time:* SMED can be used to minimize set-up times between different production batches. (Abdulmalek et al., 2006, p. 16; ElMaraghy et al., 2013, p. 641; Mahapatra & Mohanty, 2007, p. 21) By identifying all the external and internal setup activities related with the product changeover time waste can be reduced. Moreover, a cyclic planning methodology with an optimum sequence based on minimizing the set-up time can be also an optimum tool to accomplish this objective.

- *Minimize production time:* To reduce production times, cyclic planning tools can also be reliable in order to accomplish this purpose due to the high flexibility of the process and the high variability of products at this stage. By scheduling products in an optimised sequence and deciding which products should be scheduled more often than others, total production times can be reduced. (ElMaraghy et al., 2013, p. 641)

- *Minimize WiP*: This objective can be accomplished by applying proper pull production or JIT methodologies as Kanban, pulling production by customer needs (Spenhoff et al., 2014, p. 170). Another tool to reduce WiP can be producing with cells organizing products by families. Cellular manufacturing can reduce inventory levels, WiP and lead times. (Fawaz Abdullah, 2003, p. 10; King, 2009, p. 195)

4.2 Applicability in terms of production process

To make a better understanding and show all the different approaches of lean tools in semi-process environments lean tools are proposed for each different manufacturing environment defined by the product-process matrix. This is linked with the results found at Chapter 2. See figure 13

It must be highlighted that the final applicability of each tool will be dependent not only of the process characteristics and production typology, but also on each demand product portfolio. Moreover, every production step within the production chain can have different PPC tools. At figure 13 this interaction is not taken into account and it is just proposed the lean PPC concepts that can be applicable at the different production strategies that semi-process industries can have.

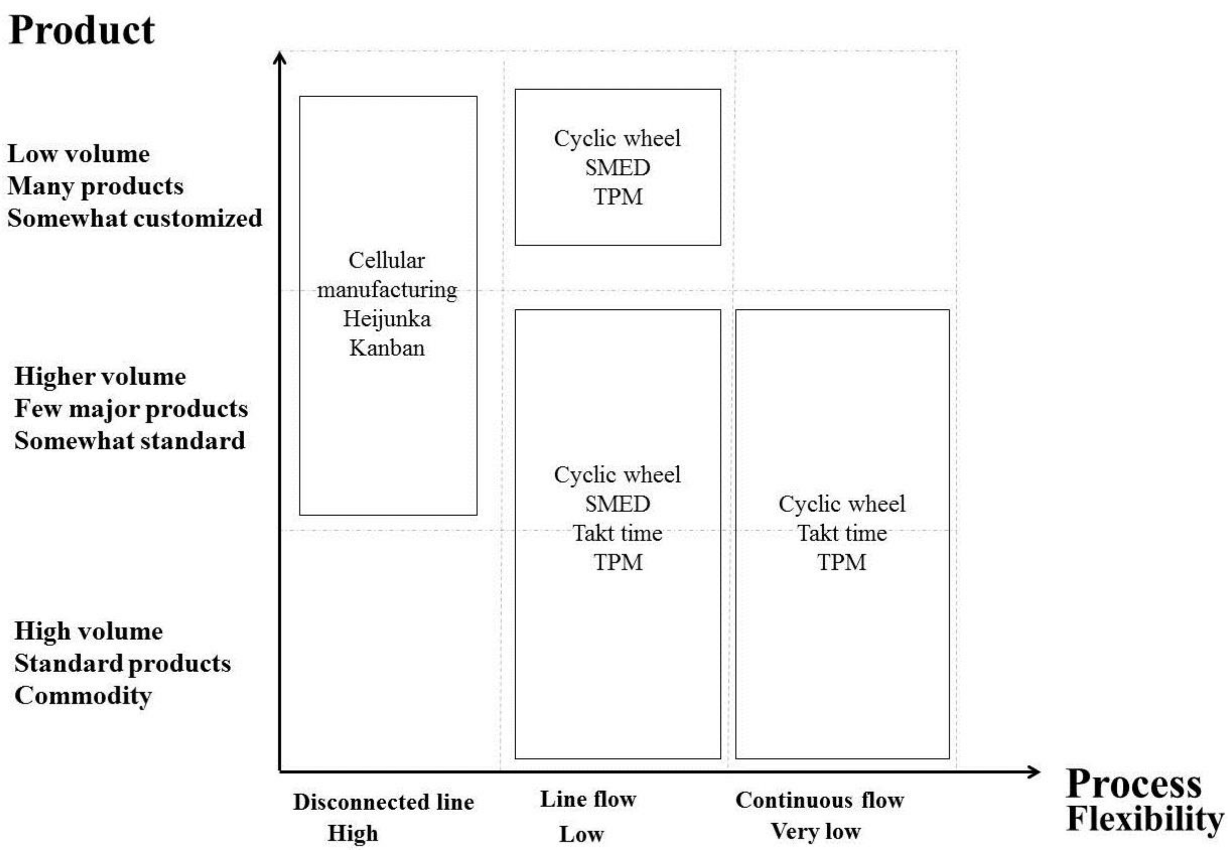

Figure 13: Applicability of lean tools in product-process matrix environments for SPI

Takt time

Takt time is better suited in stable demand environments or environments where the production quantities are stable. This is because takt time, can vary with the required amount of production required. Moreover, it is well suited for environments with few different routing. (Bokhorst & Slomp, 2010) Therefore, applicability in semi-process environments will be best suited for line processes or continuous processes. Applicability of takt time at high-volume production with continuous flow and number of limited routings can help to reduce waste time between different production steps. Applicability in high sequence dependency with changeovers if processing time is predictable such as it is with cyclic wheel planning methods. Thus, applicable to high volume low variability if changeovers are high sequence dependents.

SMED and TPM

Resource complexity of semi-process industries obstructs a straightforward application of SMED and total productive maintenance (TPM) (Pool et al., 2011, p. 194). Even being broadly applicable lean tools, their applicability may lead to inefficiency in some specific environments beneath the production processes. Thus, single minute exchange of dies (SMED) can be a useful tool to take into account at the discrete sector of semi-process industries. At this sector, changeovers are short and numerous. Therefore, small time reductions can have noticeable effects.
On the other hand, in a continuous line production process SMED as not as reliable. This is due to the fact that production is rarely stopped and products are not scheduled often.

Total productive maintenance (TPM) is best suited at production processes with high levels of equipment utilization. Environments where the reliability of the system is a fundamental key in order as not to stop the production. At continuous sectors it can be really expensive to shut down the production to repair the machine. Thus, having a straight maintenance of the equipment can be a key point to maintain production flowing. TPM can be also applied to lines with high levels of product flow. Even though service levels are lower, the application can still be beneficial.

Cellular manufacturing

Cellular manufacturing can only be applied at environments with high flexibility and parallel equipment. In semi-process industries, these environments can only be found at discrete sectors for customised products that are produced in disconnected lines. At these sectors, manufacturing with cells and producing product by families can help production achieve higher levels of flow and hence reduce throughput times.

Kanban

Applicability of Kanban methodologies is best suited for discrete sectors with sequence independency and short changeovers. Moreover, Kanban is best applied in planning environment with levelled and stable demand, stable processing times and high volume low variety of products. Thus, applicability of Kanban in semi-process environment will fit better at the discrete sector with low to high volume products and high sequence independency. In conclusion, at disconnected flow environments.

Cyclic planning methodologies

The cyclic planning methods, as cyclic wheels and Heijunka, have had considerable success as lean methods for production planning and control, which makes them particularly relevant within the context of assessing methods for production planning and control in different manufacturing environments. (Spenhoff et al., 2013, p. 212)
Thus, cyclic planning methodologies can be a key point to apply lean production planning and control methodologies in semi-process industries. These tools have a broad applicability and if well applied, they can result in high levels of services utilizations, optimum production, short lead times and reduced inventories levels.

Heijunka

Heijunka is defined as a cyclic planning lean methodology built for assembly type industries. Thus it is best applied at the intermittent and repetitive environments of semi-process industries, where short changeovers and set-up times are found. (Powell et al., 2010, p. 243) It is because Heijunka assumes that there are not changeover times, thus requires quick changeovers. This characteristic is found at the discrete sector under product job-shop or batch production strategies. Therefore, Heijunka is not applicable at the process sector of semi-process industries.
Heijunka is best applicable in disconnected lines with high volume and low variety standard products (Powell et al., 2010, p. 243), but it can also be applied in low volume and high variety of products with necessary adjustments (i.e. changeover times reduction methodologies as SMED). (Bohnen et al., 2013)

Cyclic wheels

As production in the process sector of semi-process industries is typically characterized by very time-consuming and sequence-dependent changeovers, applying cyclic wheel planning methodologies can be beneficial. It can help reduce changeover times by scheduling products in an optimized sequence. Therefore, applicability at continuous process and lines of semi-process industries can be beneficial. (Pool et al., 2011, p. 195)
At discrete sector, with intermittent flow processes, cyclic planning has been suggested as an effective way to deal with the fill rates, the inventory levels and the utilization of equipment. (Fransoo & Rutten, 1993; Noroozi & Wikner, 2014; Pool et al., 2011; Soman et al., 2004)

On the other hand, at the process sector, cyclic planning helps to improve production quality and supply-chain coordination realizing regular and repetitive sequences. (Pool et al., 2011, p. 195)
To implement it properly, decisions should be made on the length of the cycle time for each product family which is based on the set-up times, available capacity and the desired inventory levels (Fransoo & Rutten, 1993; Noroozi & Wikner, 2014; Pool et al., 2011; Soman et al., 2004) Moreover, some business changes may be needed in order to apply properly cyclic wheel planning, i.e. in the way that ERP software is used. (Packowski, 2013; Pool et al., 2011)

4.3 Applicability in terms of product demand portfolio

In semi-process industries environments lean PPC tools are not easily applicable due to the hybridity of the sector. Therefore, the applicability of lean tools can be better analysed taking into account both process structure and product demand.

Lean planning methodologies can be applied at semi-process industries at every different stage of the production process making a classification of the products produced in terms of runners, repeaters and strangers. Under this classification, there are some products that are not suited to be produced under lean manufacturing technics.

Figure 14 shows a matrix with the typical segmentation of products in terms of demand variability and demand volume at the diagonals:

- Runners: high demand variability, low volume products
- Repeaters: medium to low demand variability and demand volume
- Strangers: High demand volume and low demand variability

As highlighted before, cyclic planning methodologies can have a lot of benefits in semi-process industries. This is due to the high-changeovers properties of the process sector and the need of having a high asset utilisation on each process.

This can be properly optimised with the most optimum production sequence of products. Thus, Heijunka and different approaches of cyclic wheel planning methodologies are proposed to be applied at figure 14, together with different replenishment methodologies, within the ABC-XYZ product demand differentiation. This classification is based on the literature findings and adapted from Packowski (2013)

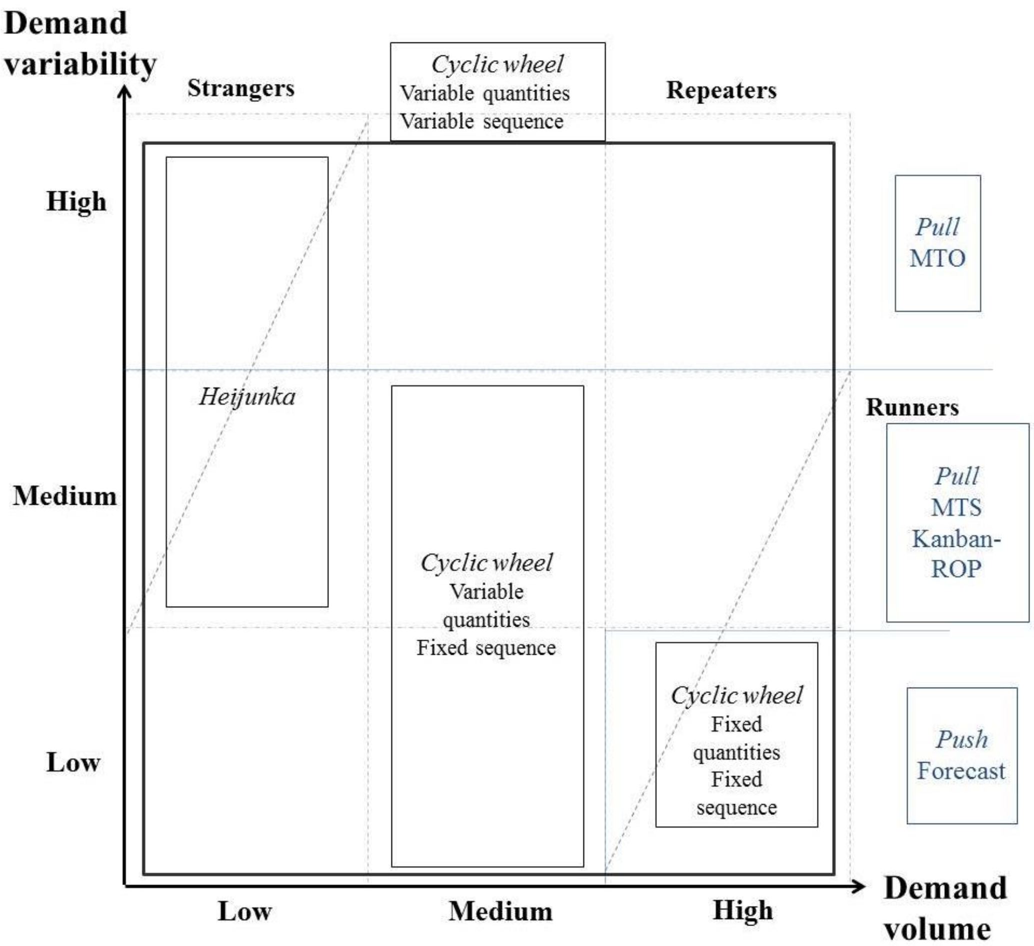

Figure 14: Applicability of lean by product demand differentiation adapted from Packowski (2013)

Runners

High volume, low variability environments will not fit for lean replenishment methodologies as production will be better planned to be forecasted with push production. This is because of the stability of demand for these products and the high volume needed to cover the demand. Thus, it is better to produce them under a forecast based methodology and stock them until the customer order arrives. Even though, lean production planning methodologies as cyclic wheels planning can be applied with fixed quantities and a fixed sequence. This will be traduced in high levels of product storage and low flexibility to react to demand variations(Packowski, 2013)

Repeaters

Products beneath this classification are best suited to be planned with cyclic wheels planning methodologies with variable quantities within a fixed sequence. Thus, demand variability allows flexibility in production quantities and hence, cycle times can vary with demand variability. This fluctuations are buffered by safety stock in inventories.(Packowski, 2013)

Pull replenishment methodologies with a MTS interaction is the best suited option for these products with medium to low variability and low to medium demand volume. In order to trigger demand from customer specifications, re-order point or Kanban replenishment methodologies can be used. Production then is triggered to replenish quantities with a ROP system with either fixed quantities or fixed time intervals.

Strangers

For low volume demand products with medium to high variability Heijunka is the best applicable planning strategy. High variability in demand leads to a big effort to develop cyclic planning methodologies as every cycle should be totally different. Thus, a planning methodology more focused on each product will fit better.

Referent to the replenishment methodology a pull replenishment with MTO fits better for high variability environments. Production is then based on real customer consumption and triggered from customer interaction. With that system there is no need to deal with safety stock levels.

High mix product demand

If a mix between all different product segmentation is found, the better approach is a cyclic wheel planning methodology with both variable quantities and sequence. (Floyd, 2010; Packowski, 2013) High volume products can be produced every cycle, so inventory levels are maintained low. Whereas, low volume products should not be produced every cycle, in order as not to have many changeovers. Instead, low volume products should be produced in large batches to cover demand for many cycles with stock. To make a distinction between products needed to be produced more often than other a differentiation by ABC product value can be done (Bicheno & Holweg, 2009; Floyd, 2010; Packowski, 2013)
From a replenishment perspective a pull MTS policy can fit better for this demand product types as production can be triggered from customer order by a replenishment signal, buffering demand variability with safety stock levels.

Chapter summary

Applicability of lean tools in semi-process industries not only depends on the process, but it also depends on the product demand characteristics. Two different frameworks have been proposed with tools applicable for each different characteristic. The first framework refers to the process dependency where distinction between continuous and discrete sector is a key point. The second framework refers to product demand characteristics. Products can be differentiated being runners, repeaters and strangers. Under this classification, planning and replenishment methodologies are proposed for every product characteristics.

Semi-process industries can take long benefit from lean manufacturing due to their process hybridity. Applicability at discrete sector is reliable and can be translated in high production flexibility with reduced levels of WiP. Whereas applicability in process sector is gaining recognition with cyclic planning approaches which can result in high levels of services utilizations, optimum production, short lead times and reduced inventories levels.

However, lean manufacturing is not applicable at all manufacturing environments. Products with high volume, low variability demand (runners) are best produced under a push replenishment methodology based on forecast. Even though, process producing these products can take benefit from lean methodologies. That is to say that these products can be scheduled with a cyclic planning wheel with fixed sequence and fixed quantities.

Chapter 5 – Summary and conclusions

5.1 Summary

Manufacturing environments are characterised by their products, processes and the customer interaction. These three entities are related with the production process (process manufacturing for non-discrete products and discrete manufacturing for discrete products), the CODP (ETO, MTO, ATO or MTS) and the production strategy (e.g. traditional job-shop, batch shop, flow line and continuous flow). The customer order interaction is the key component for the replenishment of products at every process step. Whereas the product type and production strategy have been found to be more tied with production planning strategies.

Semi-process industries are hybrid manufacturing environment industries which have to deal with different product characteristics at their process. The discretization point separates both process and discrete sector depicting this hybridity. Production processes before the DP are mainly continuous flow production of high volume standard product. Whereas, production processes after the DP can have different process layouts. Production at these discrete sectors can be either done under a connected line or a disconnected line. Product characteristics range from low to high volume with both customized and standard products. The interaction of the customer is depicted by the CODP. Production will be forecast or customer based depending on this interaction.

Traditional process-product matrix has been obsoleted due to the growth of the manufacturing industries. The literature review done has compared between different manufacturing environments for production planning and control, and process industries. It has been highlighted that nowadays, manufacturing industries environments are somewhere in between the traditional diagonal approach. Even though, as every industry is a particular case, general classifications done are few and not able to cope with all the possibilities. Thus, a comparison between all the different productions strategies found has been done trying to highlight the variety of these environments.

Lean manufacturing has a broad list of different tools applicable in all different types of manufacturing environments. When looking at the production planning and control tools, the applicability is no longer broad and even not straightforward. That is why scholars trying to apply this lean tools proposed by the TPS have been lately evolving them to new tools and concepts.

At this thesis two different frameworks in terms of production structure and product demand portfolio has been proposed based on the literature found. The first one, based on the traditional product-process matrix divides applicability of lean for every different production

All manufacturing environments can benefit from lean manufacturing tools, but not all the lean tools are applicable at every manufacturing environment. Thus, some environments can have some lean concepts applied even without being able to cope with all the lean principles. For example, products with high volume and low variability demand can be planned with a cyclic wheel methodology. However, they are best suited to have a push replenishment methodology with a forecasted production.

Lean manufacturing applicability in process and semi-process industries still falls behind discrete manufacturers. Even though, lean manufacturing methodologies are being evolved and studied in order to be applied at process sector reaching remarkable benefits (e.g. reduction in lead-times, WiP and inventory levels).

At semi-process environments the most significant tool found has been cyclic planning due to the wide range of product volumes and types that is able to cope with. Therefore, scholars such as King (2009), Floyd (2010) and Packowski (2013) have developed methodologies of application in these hybrid environments. The application can be done in either one machine or a whole line. For example, the continuous sector of semi-process industries will better apply lean planning and replenishment methodologies at hole line, whereas discrete sector can choose between both types in every machine.

5.2 Conclusions

Manufacturing environments are defined by the customer interaction, the product characteristics and the process systems. They are influenced by each other but are not totally dependent. The traditional product-process matrix highlights this influence. However, it does not reflect all the different manufacturing environments that can be found at process and discrete industries.

Semi-process industries are defined as process hybrid industries were the product produced changes from continuous to discrete at the discretisation point (DP). This defines two distinguishable sectors with different process characteristics.
Process sector is characterised with continuous production of high volume, low variety of standard products. Some other remarkable properties are low flexibility, high sequence dependency and high changeover times. Products are mostly produced under a MTS policy, thus customer interaction at this sector is low.
On the other hand, discrete sector is characterised by intermittent production. It can be done in either disconnected or connected lines. Thus, different characteristics are found on each system. In general, low to high volume of mixed variety of products with some degree of customisation. Flexibility is higher, sequence is normally independent and changeover times are lower. Thus, products can be either produced under customer specifications (MTO, ATO) or forecast based (MTS).

Semi-process industries can take benefit from the application of lean production planning and control tools in their processes. Even though, it must be remarked that not all their environments are suitable to apply lean methodologies. For example, products with high volume and low demand variability are best suited to be produced under a push replenishment methodology were production quantities are forecast based. However, these environments can benefit from other lean manufacturing tools as for example, cyclic wheel planning.

To choose between different tools a detailed analysis of the manufacturing environment must be performed. Semi-process industries can distinguish two main process sectors. The first one being the continuous process sector and the second one being the discrete intermittent sector. From this first classification different lean tools are applicable at each sector with different benefits.

- Continuous sector: Cyclic wheel planning to schedule products. Takt time to synchronize production and TPM to reach high service levels. Push replenishment methodologies are best suited for these environments.
- Discrete sector: Either Heijunka or cyclic wheel planning to schedule products. Cellular manufacturing is a possibility to reach high levels of flow and reduce throughput times grouping products and resources. TPM can be applied at lines with high machine utilisation. SMED can reduce changeover times. Finally, pull replenishment methodologies can be implemented with either MTO or MTS policies. If MTO no safety stock is needed as customer is triggered by actual customer demand. If MTS, re-order point methodologies or Kanban cards can be used to trigger production in line with consumption and levels of stock.

A close related classification can be done in process typology. Thus, different tools apply to different product types and process flexibility.

- Disconnected line: Cellular manufacturing, Heijunka and Kanban.
- Flow line: Cyclic wheel planning, SMED and TPM. Takt time pacing is best applicable if product variety is low.
- Continuous flow: Cyclic wheel planning, Takt time pacing and TPM.

Cyclic wheel planning is the best suited lean tool for semi-process industries as it is capable to cope with different manufacturing environments just varying their product sequence and cycle time. Replenishment methodologies are dependent to this classification. Pull production is the lean replenishment methodology, where production is based on customer order and triggered from downstream operations. It can be done in either a MTO (without safety stock) or a MTS policy. MTO production is triggered by actual customer demand. On the other side, MTS production is triggered by the decrease of the inventory levels. This can be achieved with applying a re-order point methodology (i.e a Kanban pull production system)

Push replenishment methodologies are not under the lean manufacturing concepts, but as said before, also a feasible option for high volume and low variability demand products. Based on the literature findings, a differentiation in terms of product demand has been found relevant. Thus, distinguishing between demand volume and demand variability products can be classified under runners, repeaters and strangers. Under this classification, the application of different production planning and control methodologies is proposed.

- Runners: Cyclic wheel planning with fixed quantities and sequence. Push forecast based replenishment.
- Repeaters: Cyclic wheel planning with variable quantities and fixed sequence. And pull MTS replenishment.
- Strangers: Heijunka planning with pull MTO replenishment
- High mix of products: Cyclic planning with variable quantities and sequence. And pull MTS replenishment.

5.3 Limitations and further research

The lack of empirical data is the main limitation of this thesis is. The application of all the concepts studied is not straightforward and as it can signify changes on the production process. All the concepts studied and developed here are interpretations of the literature found related with these topics. The results of this thesis are based on the contrast of the literature of lean manufacturing applicability in process industries.

The interaction between two customer orders at the same production process has not been taken into account as it depicts a more difficult environment. This hybrid environments can be seen as having a push-pull replenishment methodology where the production is forecast based at the beginning and turned to customer based at some point. The challenges include the cost of low utilization of equipment, the possibility of decoupling the production process and adding buffers, the capacity of the buffers and the selection of intermediate products.(Caux et al., 2006)

It can be interesting for further work to see how to apply these hybrid push-pull systems, and all the manufacturing possibilities they can offer. Scholars as Geraghty and Heavey (2005) and Powell, Riezebos, and Strandhagen (2013) have already studied these hybrid systems where pull production is combined with forecast based methodologies as ERP systems.

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