MSc Program
Engineering Management

An Evaluation of the Applicability of Lean Methods in an Engineer-to- Order, High-Mix-Low-Volume Manufacturing Environment – A Case Study in the Heavy Industry

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Dr.-Ing. Thomas Duda

Yvonne Wenzel

11936531

Vienna, 28.03.2021

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Affidavit

I, **YVONNE WENZEL**, hereby declare

1. that I am the sole author of the present Master's Thesis, "AN EVALUATION OF THE APPLICABILITY OF LEAN METHODS IN AN ENGINEER-TO- ORDER, HIGH-MIX-LOW-VOLUME MANUFACTURING ENVIRONMENT – A CASE STUDY IN THE HEAVY INDUSTRY", 100 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract: Master Thesis Engineering Management Intake 2019-2021

Student Name: Yvonne Wenzel

Matriculation Number: 11936531

Title: An Evaluation of the Applicability of Lean Methods in an Engineer-to-Order, High-Mix-Low-Volume Manufacturing Environment – A Case Study in the Heavy Industry

The study reviewed the applicability of Lean methodology in the engineer-to-order, high-mix-low-volume environment. It asked the question of whether Lean practices find applicability in an engineer-to-order environment in the same way as in a mass production or in low-mix-high-volume environments. Furthermore, it looked to explore whether Lean practices can be implemented in the classical way in an engineer-to-order operation or whether adaptations to Lean practices are necessary.

As Lean methodology originated in the automotive industry it is well suited for serial productions in the low-mix-high-volume field. Therefore, the question arises how well Lean methodologies are suited to complex and dynamic environments in the high-mix-low-volume field. Lean concepts were reviewed followed by a literature review with a focus on the engineer-to-order, high-mix-low-volume applications. In particular, the approach of Lean bundles was examined and applied to the case study.

The study showed that for Company A, the implementation of Lean practices in a holistic and integrative way across the organisation has led to tangible performance improvements. The Lean practices were adapted to suit the requirements of Company A. A considerable level of customisation was required to adjust classical Lean practices to fit the more flexible and dynamic needs of company A.

In line with Lean philosophy expectations, the Lean restructuring programme did considerably reduce waste (*muda*) across the organisation and allow for a better production flow through smoothing of demand (*mura*), in turn reducing the overburdening of staff and of equipment (*muri*). It can therefore be concluded that

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the implementation of Lean practices can also lead to performance improvements in the more dynamic and less stable environment of engineer-to-order companies.

The study's limitation is that the research was only conducted on one single case study. Therefore, the findings may not be entirely generalisable, where other engineer-to-order companies producing different products and operating under different conditions may require a different approach. Also, the customisation of Lean practices may conceivably require customisation of different practices with a different focus.

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1. Introduction

Lean manufacturing concepts have dominated the manufacturing field for the last decades and are considered a must in modern, efficiently organised production facilities. Lean management is widely seen as enhancing the performance of companies in order to ensure survival on increasingly competitive global markets. However, as Lean concepts originated in the automotive industry based on mass production concepts or on the production of very large series, the obvious question arises of whether concepts that have been designed for manufacturing processes based on low variability of products, processes as well as demand and large volumes of the same product can be meaningfully applied to production environments where the markets and the customers value purchasing highly customised products in very low quantities.

1.1. Problem Definition

With the wide variety of Lean tools available, companies need to consider which tools are most useful in their specific environment and for their particular application. As resources are scarce and time is limited, the management of an organisation needs to carefully evaluate what to prioritise in order to have the biggest impact and the greatest overall gain.

There is consensus in Lean literature that Lean methodology is both applicable and supporting performance improvements also in high-mix-low-volume, engineer-to-order environments. However, the available literature is scarce on identifying which lean tools find application in a complex manufacturing environment with high variability and low volume. Consequently, the question arises which Lean tools can be usefully employed in high-mix-low-volume industries.

1.2. Research Questions

- Which Lean tools are applicable in a high-mix-low-volume, engineer-to-order manufacturing company? Are there Lean tools that are not suitable to high-mix-low-volume, engineer-to-order manufacturing?
- Can Lean tools be customised to better suit a high-mix-low-volume environment to improve performance

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2. Research Methodology

It is proposed to review available literature on Lean concepts in general as well as available literature on lean concepts in an engineer-to-order, high-mix-low-volume manufacturing environment. The insight gained from the literature review will be applied to a case study of Company A, which operates in an industry setting of engineer-to-order with a focus on high-mix-low-volume.

Subsequently, the study will evaluate the industrial environment of high-mix-low-volume manufacturing companies. Particular focus will be put on the need for complexity in a dynamic industrial environment. Next, the evolution of Lean methodology in a manufacturing environment, with a particular focus on the current state of research conducted in high-mix-low-volume industries, will be examined. An applicable concept based on the use of Lean 'bundles' (Shah & Ward 2003; Azadegan et al. 2013; Birkie et al. 2016; Birkie, et al. 2017) will be proposed.

In a further step, an overview of the company under evaluation in the case study will be given. It will be reviewed which Lean bundles have been used, and their outcome on overall performance will be appraised. In a next step, the results of the application of the Lean 'bundles' considered on the specific company in the case study will be specified. Finally, a conclusion of the study will be provided.

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3. Literature Review of Lean Concepts in Complex and Dynamic Environments

3.1. Complex and Dynamic Industrial Environments Requiring Flexibility

The manufacturing industry has evolved considerably over the centuries. For many centuries craft production was the norm. Generally, one very skilled person made one product by hand customised to the requirements of the client (Stevenson, 2013: p.21). This was highly inefficient and did not offer the advantages of economies of scale. It also did not allow for easy reproduction of an identical item. There was an inevitable need to evolve.

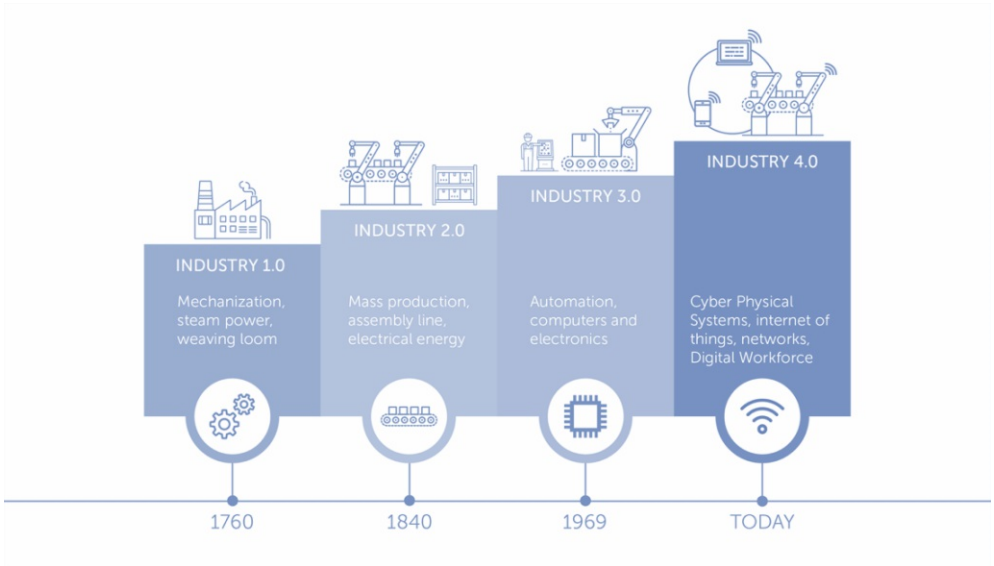

Figure 1: Stages of Industrial Revolution,

(https://www.automationanywhere.com/images/blog/RPA-blog_A.png)

So, over the last three centuries manufacturing has moved from the craftsmanship approach to highly complex and specialised production systems today, which have culminated in the 4th Industrial Revolution. Figure 1 provides an overview of all four industrial revolutions, or Industry 1.0 to 4.0. The first industrial revolution was considered to be the mechanisation of production powered by steam or water in the concept of the first mechanical loom in Great Britain in 1784. The second industrial revolution was the technological revolution, making mass production possible through the use of electrical power and the division of labour which allowed specialisation. The first use of a conveyor belt is seen to have been employed in the slaughter houses

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of Cincinnati in 1870. Automation and digitalisation defined the third industrial revolution, moving from analogue electronic technology to digitally connected, centrally controlled machines and objects, where the first programmable logic controller was considered to be Modicon 084 in 1969. The fourth industrial revolution, also known as Industry 4.0, is based on digital networks, robotic process automation and data exchange using the Internet of Things, cloud computing and cyber-physical systems (Figure1). (Schneider 2019, 39) The concept of Industry 4.0 was first presented at the Hannover fair in 2011 and is a collaboration between the German government, the private sector and academia (Buer et al. 2018: 2925, www.plattform-i40.de).

Since Lean Manufacturing evolved from the automotive industry through the Toyota Production System (TPS), Lean concepts are mostly geared towards mass production or large series. The automotive industry is based on low-mix-high-volume production, where products are relatively standardised and volumes are reasonably large. However, most of global manufacturing is focused on providing high-mix-low-volume products (Heizer et al. 2017: 282). Mass produced products are often made-to-stock, where quantities of the same product can be ordered and shipped immediately. A faster obsolescence of products due to shorter life cycles can lead to waste and financial loss when the products are no longer in demand. As Figure 2 shows, engineer-to-order companies operate at the far end of the high-mix-low-volume and customisation scale, while make-to-stock and mass production companies are at the low-mix-high-volume end of the scale with little to no customisation.

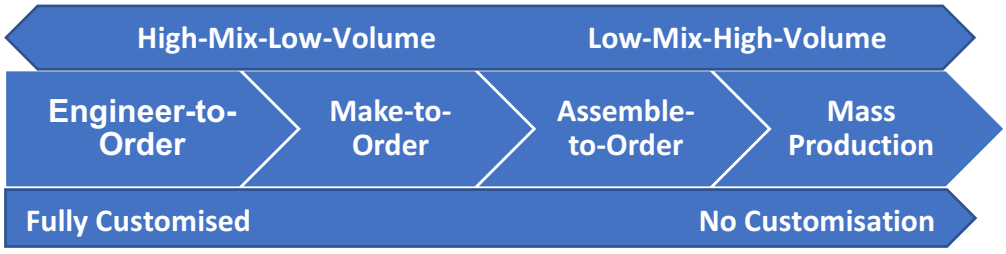

Figure 2: Levels of Customisation

But many products are made-to-order, as customers look for products that are more customised. This generally means that customers must accept a longer lead time. In an engineer-to-order environment, customisation goes one step further where the customer provides predefined specifications, and the customer and the manufacturer develop the desired product together. In an engineer-to-order environment, the high

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level of customisation is the value offered by the manufacturer to his customer. Where possible companies attempt to modularise the components of the final product in order to shorten lead times and reduce complexity and variability. But often that is not possible, as product sizes, parts, materials and processes vary considerably. Figure 3 highlights how a low level of standardisation allows larger volumes to be produced in continuous processes (e.g. oil refinery, high & medium density fibre boards) or large batches (e.g. automotive, printed circuit boards for the B2C market). In contrast, a low level of standardisation coupled with small volumes leads to intermittent processes, where products are manufactured in batches (e.g. printed circuit boards for robots) or as individual projects (e.g. heat exchangers for petrochemical industry, where one order can take more than a year to produce).

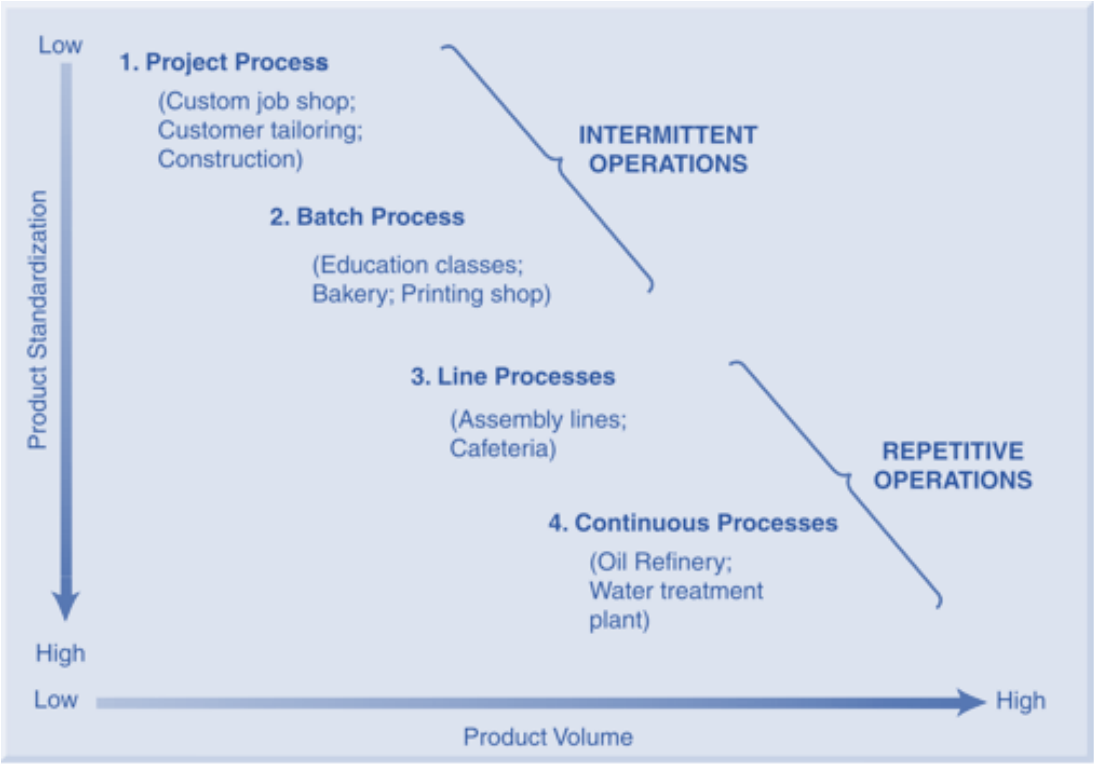

Figure 3: Types of Processes Based on Product Volume and Product Standardisation (Reid & Sanders 2013: 71)

Where there is a demand for highly customised products in small volumes, there is a need for high variability and flexibility on the part of the manufacturer. This runs counter to the lean thought of reduction in variation and increase in standardisation. As customised products often also require varied processes with different sequences, following the Lean concept of flow is also hindered. Furthermore, in high-mix-low-

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volume companies demand planning is generally also more complex as large numbers of small orders makes forecasting and consequently levelling more challenging. An exception to this rule is the case of mass customisation where often highly automated processes make it possible to produce large numbers of customised products (see Figure 4). This is also seen as a potential application for Industry 4.0 where fully networked systems will allow for higher levels of customisation without the additional burden of higher cost and higher inefficiencies related to change requirements in the production process (Gonçalves et al. 2020: 1477; Rüttimann & Stöckli 2016: 488). Industry 4.0 can solve the digital aspect of variability through networked systems where computer-aided design (CAD) or computer-aided manufacturing (CAM) can eliminate the time required for digital uploads. But the physical aspect for the need to exchange dies and set up machines still remains unresolved. Consequently, in contradiction to Lean thinking an element of waste remains.

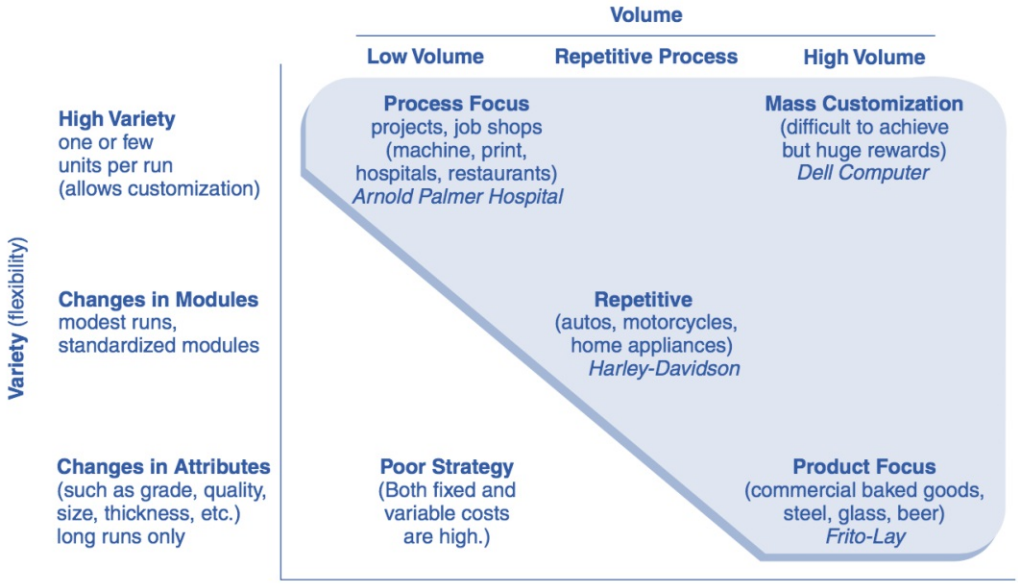

Figure 4: Process, Volume and Variety (Heizer et al. 2017: 282)

As the customisation of the product in an engineer-to-order company adds value to the customer, it is often an order confirmation qualifier (Powell et al. 2014: 573). So, the reduction in variability, one goal of Lean, is not desirable in an engineer-to-order set up.

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Engineer-to-order environments lead to increased levels of uncertainty across a number of attributes such as product specification and mix, process specification as well as volume (Powell et al. 2014: 572). It can therefore be argued that engineer-to-order companies operate in a more dynamic and complex environment, where a higher level of responsiveness is required to win an order leading to a higher level of flexibility. What Powell sees as uncertainty Holweg defines as responsiveness in the form of the "ability to adapt" or respond on the three dimensions of product, process and volume (Holweg 2005: 606 & 613). One way of allowing for this higher level of responsiveness is to permit uncommitted capacity, which if not taken up, will lead to waste, contradicting a stated key aim of Lean (Seven Wastes, Ohno 1988, Chapter 2).

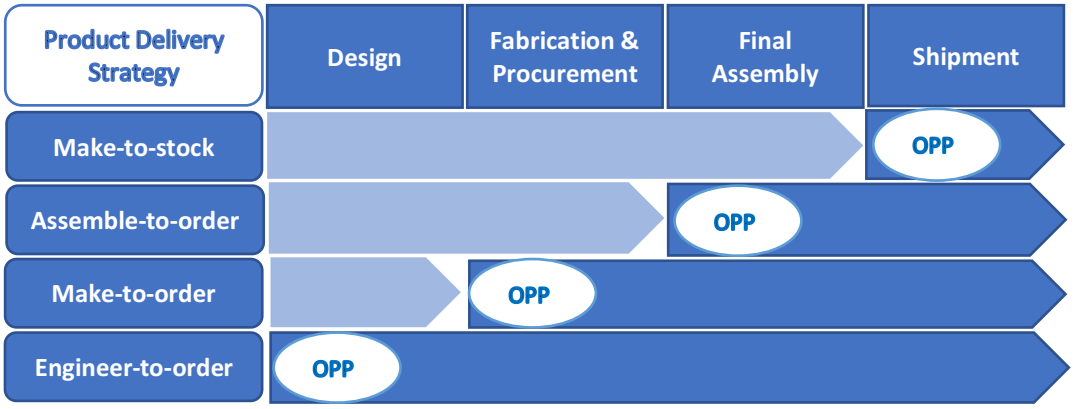

Figure 5: Product Delivery Strategy & Order Penetration Point, (Olhager 2003: 320)

Critical to a manufacturing or product delivery strategy is the order penetration point (OPP) also described as the customer order decoupling point (CODP). Olhager defines the order penetration point as "the point in the manufacturing value chain for a product, where the product is linked to a specific customer order" (Olhager 2003: 320). Powell (2014) states that the "customer order decoupling point separates the part of the material and information flow that is based on firm customer orders from the part that is based on forecasts and speculation" (Powell 2014: 572). Holweg (2005) links the decoupling point to the P/D ratio where P is the production system's response time and D is the customer's willingness to wait. Therefore the "P/D ratio also defines the de-coupling point in the system at the point where the customer demand signal feeds into the supply chain" (Holweg 2005: 605). The authors look at the same issue from different perspectives. All aspects are equally significant for an understanding of the company offer in respect to the volume-variety mix and the relevance of Lean

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concepts. Figure 5 shows that in the high-mix-low-volume context generally associated with make-to-order or engineer-to-order approaches, the decoupling point is early or to the left of the value chain meaning that the cut-off point for customisation happens early in the process making the reduction of waste more difficult as far as the production planning.

In an engineer-to-order environment, flexibility, lead time and customisation are order winners. In a make-to-stock market, companies compete on price (see Figure 6). Olhager points out that there is a trade-off between "maximum manufacturing efficiency that dominates the pre-OPP operations and … minimum inventory investment that dominates the post-OPP operations" (Olhager 2003: 328). As far a production strategy is concerned Olhager sees a more flow-oriented approach upstream and a more job shop oriented approach downstream. It is therefore evident that the order penetration point has a bearing on the approach to Lean implementation. The earlier the order penetration point in the value chain, the earlier a customized approach to Lean must be considered.

Job Shop Strategy	Post-OPP	OPP	Pre-OPP	Flow Strategy	
Disadvantages	**Reasons for Shifting the OPP Backward**	**Competitive Advantage**	**Competitive Advantage**	**Reasons for Shifting the OPP Forward**	**Disadvantages**
Longer delivery lead times and reduced delivery reliability (if production lead times are not reduced) Reduced manufacturing efficiency (due to reduced possibilities to process optimisation)	Increasing the degree of product customisation Reduce the reliance on forecasts Reduce or eliminate WIP buffers Reduce the risk of obsolescence of inventories	Product range Product mix flexibility Quality	Delivery Speed Delivery Reliability Price	Reduce the customer lead time Process optimisation (improved manufacturing efficiency)	Rely more on forecasts (risk of obsolescence) Reduce product customisation (to maintain WIP and inventories levels) Increase work-in-process (due to more items being forecast-driven)

Figure 6: Order Penetration Point and Market, Product & Manufacturing Strategies, (adapted from Olhager 2003: 325-326)

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3.2. Lean Concepts

Lean methodology remains one the most influential concepts for the manufacturing industry in the last decades (Shah & Ward 2007: 785-786). It has fundamentally shaped the way companies approach the way they operate. While the concept originated in the way Toyota company approached its production system coined the Toyota Production System (TPS), the approach was popularised through the seminal work of Womack, Jones and Roos entitled 'The Machine that Changed the World' (Womack et al. 1990). While the Toyota Production System had been under development in the form of continuous learning since right after the Second World War, it only became known in the West in the mid-seventies due to the first oil crisis that forced Western automotive companies to reconsider how they operate (Holweg 2007: 422-423). The term Lean on the other hand was coined by John Krafcik, who in the late 80s was on the Massachusetts Institute of Technology (MIT) team of James Womack when the research for the book 'The Machine that Changed the World' was conducted (Womack 2002: L4). However, the brain behind the Lean approach that emanated from Toyota company was Taiichi Ohno who had first started working in the spinning and weaving business that was the origin of Toyota company. In 1943 he joined the automotive arm of Toyota company as production manager where his unconventional view from a different industry allowed him to approach the automotive production without preconceived ideas (Holweg 2007: 422). Thus, was the Lean methodology, stemming from the Toyota Production System, born.

3.2.1. Overview of Lean Methodology

Curiously the term 'Lean' does not have a uniform definition that is applied consistently despite its widespread use (Shah & Ward 2007). This lack of a coherent definition also applies to the individual components parts that make up the Lean methodology such as just-in-time (JIT), total productive maintenance (TPM) or total quality management (TQM) (Shah & Ward 2007: 788 & 800). It is widely argued that taking only the component parts and implementing them in an organisation leads to inferior results compared to implementing Lean methodology as a complete socio-technical system (Shah & Ward, 2007: 800; Sahoo & Yadav 2018: 392-393, Birkie et al. 2016, Birkie 2017). Even the implementation of more than one component improves the result disproportionately compared to the introduction of only a single

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component part (Braglia et al. 2019, Bortolotti et al. 2019). In this context Lean is seen as a fundamental philosophy (Powell et al. 2014: 572, Seth et al. 2017: 404).

Shah and Ward propose the following definition

> "Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability." (Shah & Ward 2007: 791)

This definition includes both external aspects with a focus on customer and supplier as well as the internal aspects with a focus on relationships across functions of the organisation. Furthermore, a focus on hard and soft practices has been proposed (Bortolotti et al. 2015: 184). Hard practices are considered to be technical and analytical aspects with a view to Lean tools. Soft practices have people at their core and look more towards Lean as a philosophy.

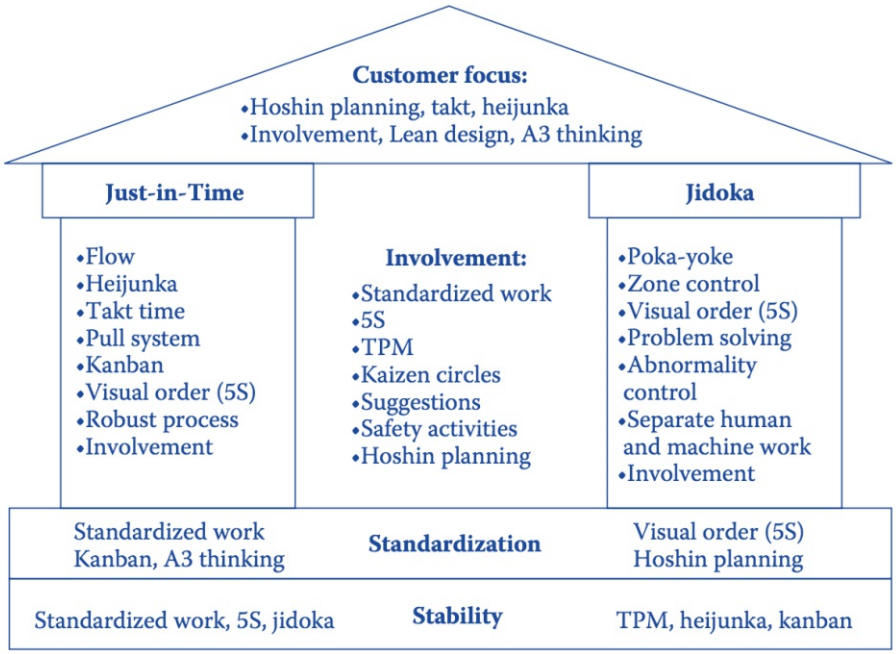

Figure 7: House of Lean based on the Toyota Production System (Dennis 2015: 53)

The overarching goal of Lean philosophy in the Toyota Production System is the increase in the generation of value to the customer (Figure 7). The system has the just-in-time (JIT) approach and the autonomation, or *jidoka*, as its two supporting pillars. At the heart of the Toyota house of Lean are people and their involvement in the organisation and the processes through continuous improvement (*kaizen* circles),

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safety activities or providing suggestions to management that will have an impact on change. The house of lean builds on the double foundation of standardisation and stability, the two elements that cannot be reached in a high-mix-low-volume setting in the same way as in a low-mix-high-volume set up.

The basis of Taiichi Ohno's approach to manufacturing was to recognise and eliminate waste. He identified seven sources of waste, or *muda,* as anything that does not add value to the customer:

- **Overproduction** – producing more and at an earlier time than the customer requires
- **Waiting** – waiting for machine repairs, for parts, for tools, for packaging, for delivery
- **Transportation** – transporting anything for more than once and further than necessary is wasteful
- **Excessive processing** – adding features that the customer did not require or providing higher quality than necessary
- **Inventory** – having more material in store requires space and clutters the production
- **Excessive motion** – work stations that are not designed ergonomically or any situation where more motion than necessary becomes unavoidable
- **Defects** – repairs, rework, scrap, recalls, repackaging and worst of all customer claims due to defective products are a source of waste

In recent years an additional eighth type of waste has been identified (Hill 2015: 16). Although it can be argued that while it was not explicitly identified by Taiichi Ohno, his focus on teamwork and the person in the organisation makes this last waste an element that was implicitly included in his Lean approach.

- **Human talent** – it is wasteful not make use of human potential when and where available

The basis of a just-in-time approach is the production and delivery of only what is needed and when it is needed by the customer. It is built on customer orders 'pulling' the production of an item through the manufacturing system, i.e. it moves from upstream to downstream triggered by the customer order. This reduces inventory to a minimum within the line as well as within warehouses. For each part in the system a strictly limited quantity of *kanban* cards is in circulation between work stations,

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where a shortage uncovers a previously hidden problem that can then be resolved by corrective action. *Heijunka*, or load levelling, smooths incoming orders by mixing different products in small quantities necessitating quick changeovers. This ensures the production flow is in sync with the takt time where the production rate matches the rate of customer orders.

Autonomation, or *jidoka,* a combination of the Japanese characters of self and movement, is also termed as "automation with a human touch" (Hill 2012: 178) describing how the manufacturing line will be stopped by a human when an error occurs to ensure that errors are immediately dealt with and will consequently decrease. *Poka yoke*, or error-proofing, and 5s (sort, set in order, shine, standardise, sustain) are visual management tools designed to make error identification and consequently elimination easier. The idea of *jidoka* has now extended to mean automatic line shut down when an error occurs, often involving man and machine. This means that errors and quality issues will be removed at source.

At the heart of the Toyota Production system is teamwork and a respect for people. Womack, Jones and Roos describe it thus

> "…there exists some sense of reciprocal obligation, a sense that management actually values skilled workers, will make sacrifices to retain them, and is willing to delegate responsibility to the team." (Womack et al. 1990: 99)

Through involving people, waste can be reduced in the *gemba*, or the 'real place' where the work is done and value is created. This highlights the importance of the soft practices and the need for seeing Lean as a philosophy rather than just a set of tools. In organisations where a culture of cooperation, teamwork and respect exists, Lean has a higher impact on overall performance. This extends to the external relationships with customers and suppliers in order to benefit from the maximum of Lean potential. The culture of *kaizen,* meaning change for better or 'continuous improvement', focuses on incrementally reducing waste and adding value through the involvement of each and every employee.

The 'housekeeping' approach of 5s is a necessary tool of which a basic level needs to have been implemented before a meaningful Lean implementation can be considered. Heizer et al. maintain that 5s assists a culture of continuous improvement and is a useful tool with which employees can easily identify (Heizer et al. 2017: 639).

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Standardisation helps to streamline the organisation and its processes. A good standard is achieved when the processes, machines, materials and labour are combined in the most efficient and therefore the least wasteful way. When a common standard has been implemented it is also easier to identify waste, or what deviates from the standard. Here tools such as A3 thinking, where one sheet of A3 paper is used to evaluate a problem, and *hoshin kanri* (*ho*-direction, *ri*-needle, *kan*-control, *ri*-reason), or the "management compass that directs all parts of the organisation towards a common goal" (Hill 2012: 162).

Equally important in the Toyota Production System is stability of processes, materials, machines and labour. Standardised work instructions, production process levelling and removing errors at source all assist in providing stability. Total productive maintenance (TPM) is aimed at the stability of the machine park with a focus on predictive and preventive maintenance rather than emergency repair. Elements of total productive maintenance include overall equipment efficiency (OEE), mean time to repair (MTTR) and mean time between failure (MTBF). Waiting for machine availability is an obvious source of waste in the form of waiting.

In a Lean production environment, takt time is an important concept that needs to be distinguished from cycle time and throughput time. Takt time originates from the German word *'Takt'* meaning to "beat a rhythm" (Cambridge German English Online Dictionary). A Toyota delegation had visited German manufacturing companies pre-war where they had witnessed the concept of 'Produktionstakt', which they later applied in their own plant and which is what is now known as takt time (Holweg 2007: 241). Takt time defines the pace of the production and is in pace with customer demand (Hill 2012: 353). Cycle time is defined as the time for one unit of work, or between the completion of processes, or of production steps (Hill 2012: 95). Applied to Lean that would mean the ideal target cycle time is the takt time as it is aligned with the customer demand rate. The throughput time or production lead time is the cumulative time required for one unit to be produced from start to finish. It is, therefore, the end time minus the start time for one unit. (Hill 2012: 95)

As value creation and the abolishment of waste is such fundamental aspect of Lean methodology in the Toyota Production System, the search for value or the search for waste is an obvious next step. The concept of value stream mapping (VSM) originated

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from Toyota Motor Company (Hill 2012: 376) but was first introduced in English in the book 'Learning to See' by Mike Rother and John Shook (Rother & Shook 1999). The approach was subsequently taken up by other authors and is now pervasive. A value stream map is a graphical analysis of all processes within the supply chain of a company evaluating where value is added and where no value is added. This needs to be done for each product or product family based on lean principles and benchmarks. It helps to identify which processes a company needs to rethink or eliminate. An often quoted five step approach is the identification of value, the mapping of the value stream, the design for flow, the pull implementation and the achievement of perfection (Womack & Jones 2003: Part 1).

It is striking that in the last four decades Lean has remained largely unchanged as well as consistently relevant (Womack 2002, L5). While research into Lean is ongoing, it mostly hones in on specific details of Lean management and clearly is still topical in academic circles.

One notable addition to Lean thinking is Lean Six Sigma. The term six sigma actually originates from statistical process control methods, where six sigma states that if the process is six standard deviations from the process mean and the nearest specification limit, then virtually no items will fall outside the specification. In practical terms, this means that out of one million parts produced only 3.4 parts are defective (Kosieradzka et al. 2011: 64) leading to the 'parts per million definition'. In other words, six sigma seeks to reduce process variability. This is a concept that only finds partial applicability in a high-mix-low-volume environment where many different products requiring many different process are necessary.

In 1986 the method was developed at Motorola and later adopted by GM in 1995 (Roser 2017: 349). The basic statistical tools were expanded to reflect that the concept incorporates many lean tools and approaches. It is argued that six sigma is actually an extension of total quality management (Kosieradzka et al. 2011: 63). The definition of Lean Six Sigma is that it is "a formal process improvement program that combines six sigma and lean thinking principles" (Hill 2012: 192). It can be argued that Lean Six Sigma puts more focus on the use of standardised statistical tools and formalized roles, such as 'green belt', 'master black belt' and 'champion', while Lean in the sense of Toyota Production System is more of an integrative philosophy. Often

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the DMAIC (Define, Measure, Analyse, Improve, Control) improvement cycle is associated with Lean Six Sigma (Kosieradzka et al. 2011: 64, Hill 2012: 193).

One area of interest that has a bearing for the future is the link between Lean methodology and the dawn of Industry 4.0. Numerous studies have highlighted the link between Lean and the introduction of Industry 4.0 concepts (Bittencourt et al. 2019). Researchers verge from suggesting Lean as a prerequisite of Industry 4.0 to Lean as a promoter of 4.0 to Lean as synergetic with Industry 4.0 (Buer et al. 2018: 2924-2925, Mayr et al. 2018: 623). Research goes as far as linking specific Lean methods to specific Industry 4.0 tools (Mayr et al. 2018: 624). Buer et al. state that "Industry 4.0 and lean manufacturing share the same general objectives of increased productivity and flexibility" (Buer et al. 2018, 292). This may have a beneficial effect on high-mix-low-volume industries as Industry 4.0 promises higher levels of customisation without the related cost increase. The verdict is out not least because of the considerable investment, time and effort required for a digitalisation strategy.

3.2.2. Lean Concepts in the High-Mix-Low-Volume, Engineer-to-Order Environment and the Current State of Literature

It is widely agreed in academic circles that, as Lean methodology has emerged from the automotive industry with a focus on low-mix-high-volume, it cannot be applied in the same way to a high-mix-low-volume environment (Adlin et al. 2020: 1371-1372, Tomašević et al. 2020: 1-2, Birkie & Trucco 2016: 347, Birkie et al. 2017: 458, Holweg 2005: 604, Powell et al. 2014: 571). The uncertainties that companies face in a high-mix-low-volume environment make it difficult to directly apply some of the Lean concepts. Lean foundations such as standardisation and stability are difficult to impose on an environment where flexibility and dynamism are prized by the customer and are considered an order winner. Consequently, scholars have analysed the high-mix-low-volume environment and evaluated Lean tools for their applicability in less standardised and stable settings.

The literature collected on high-mix-low-volume manufacturing environments focusing on Lean methodologies spans a wide range of topics providing a broad overview (Figure 8). Research verges from comprehensive literature reviews to the in-depth analysis and evaluation of specific, often shop floor related, tools. Scholars have looked into Value Stream Mapping (VSM) as a first step into Lean

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implementation. Research has investigated the environment of high-mix-low-volume to identify what makes it different from mass or serial production. Some scholars have taken up Lean bundles and applied them to the characteristics of high-mix-low-volume environments, while others have focused on one or a combination of Lean bundles, such as Total Productive Maintenance or Total Quality Management. Generally, Lean is seen as overall also fitting the high-mix-low-volume and engineer-to-order industries. However, scholars suggested that customisation helps to make tools and concepts more suitable. Additional instruments may be included to enhance the overall fit.

The studies of Tomašević et al., Adlin et al. and Shah and Ward (2007) provide a comprehensive literature overview over the state of Lean management in a high-mix-low-volume setting (Tomašević et al. 2020; Adlin et al. 2020, Shah & Ward 2007). Tomašević et al. found that most studies are directed towards narrowly defined tools and many have a focus on practice and pay little attention to theory development. The studies are often targeted towards internal processes with a particular interest in shop floor improvements while more holistic approaches are underrepresented. They also highlight the challenge of generalisability of findings due to the diversity of operations. Adlin et al. have found that while Lean methodologies are applicable in the high-mix-low-volume environment, "existing lean practices are applied with sound customisation and a combination with (*sic*) applicable methods, tools and techniques originating outside from the lean toolbox" (Adlin et al. 2020: 1376). Furthermore, they have identified that among the stand-alone tools Value Stream Mapping (VSM) was found to be the practice that was most applied. No particular combination of Lean tools appears to be dominant in bundle application (Adlin et al. 2020: 1375-1376). Shah and Ward analysed the existing literature with a view to their consistency of terms and concepts and found that the definitions are very general and have become more expansive over time (Shah & Ward 2007: 788). They also discovered that Lean production was approached from either one of two ways: the philosophical approach "related to guiding principles and overarching goals or from the practical perspective of a set of management practices, tools, or techniques that can be observed directly" (Shah & Ward 2007: 787).

Given the unavoidability of complexity, dynamism and the necessity for responsiveness and flexibility in a high-mix-low-volume setting, it is surprising that, while the literature review was not structured but selective, the number of studies

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evaluating the impact of the environment on Lean methodology in high-mix-low-volume is not more extensive. Holweg found that agility of the supply chain is defined by the three basic variables of volume, product and process that allow responsiveness to customer orders. He also identified that there is not one 'holy grail' concept to order fulfilment – i.e. customer value implementation – given the multiple contingency factors involved. Rather, a strategy needs to be moulded around a company's specific realities (Holweg 2005: 617-618). Azadegan et al. show that the implementation of Lean approaches assists in mitigating the difficulties that are brought about by environmental complexity and dynamism. Azadegan et al. define environmental dynamism as the "rate and volume of change in the environment" and complexity as being "caused by the multiplicity of inputs and outputs" (Azadegan et al. 2013: 194). Expectedly environmental dynamism negatively affects the benefits derived from Lean operations. Curiously the study shows that environmental dynamism positively impacts the benefits from the implementation of Lean purchasing on performance. The authors speculate that this may be related to improved supplier relations assisting the mitigation of environmental uncertainties through information sharing (Azadegan et al. 2013: 205). Bortolotti et al. examined the adoption of specific organizational culture attributes and their impact on high performance manufacturing in Lean plants. They found that successful Lean companies had adopted soft Lean practices, such as small group problem solving, employees' cross-functional training, supplier partnerships, customer involvement, and continuous improvement, more extensively than unsuccessful Lean plants. They also established that this does not apply in the same measure for the adoption of hard Lean practices such as technical and analytical tools which are "essential but not differentiating" (Bortolotti et al. 2015: 194-195).

Strandhagen et al. (2018) explored how operational applications of Lean in an engineer-to-order environment using an adapted Value Stream Mapping (VSM) approach can identify sources of waste that affect lead time. The authors concluded that several sources of waste that affect lead time exist, in particular in non-physical processes such as the sales, engineering and project management processes. They have defined a number of independent guidelines to mitigate the adverse effects of waste in order to reduce lead time and have demonstrated that "principles of Lean production can be highly relevant in identifying and eliminating sources of waste also in ETO operations" (Strandhagen et al. 2015: 133). Seth et al. maintain that Value Stream Mapping (VSM) application-based Lean approaches do not differ

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fundamentally in simple or complex environments. Due to the intermittent, parallel and independent nature of complex production environments, time measurements are difficult. The authors propose broad guidelines based on the five points Value Stream Mapping approach (value, value stream, flow, pull, perfection) to facilitate Lean (Seth et al. 2017: 414-415). Matt (2014) has evaluated best practice guidelines in using adapted Value Stream Mapping in an engineer-to-order environment. He has found the synchronization points ahead of merge activities and the separation of customer orders into appropriate manufacturing orders to be of particular relevance (Matt 2014: 346).

The vast majority of research focuses on shop floor activities of which most examine production control topics. This is especially relevant as this is a key area of divergence from mass production or even low-mix-high-volume manufacturing. Becker et al. propose a new overall equipment efficiency (OEE) measure to better account for the variations that define the high-mix-low-volume operation. As in a non-repetitive context there are multiple categories of products, there are also multiple defective products, making defect calculation difficult. To overcome this, machining equipment effectiveness (MEE) therefore takes the cost of defects as the basis of calculation (Becker et al. 2015: 420). Bohnen et al. suggest to divide products into families based on runner, runner/stranger and stranger categories based on ABC clustering. A family specific levelling pattern is then envisaged to allow distinct production runs and capacity planning (Bohnen et al' : 57-58). Bortolotti et al. examined how Just-In-Time (JIT) practices can be introduced in a non-repetitive context, and then evaluated their impact on efficiency and performance. They found that customisation does not diminish the link between Just-In-Time (JIT) and a company's performance both in relation to efficiency and responsiveness. Concepts such as variety reduction programmes, modularity and mass customisation can resolve undesirable effects of customisation. However, demand variability does reduce the positive effect of Just-In-Time on responsiveness, while it does not necessarily adversely affect the impact on efficiency (Bortolotti etl. 2013: 1125-1126). Braglia et al. introduce a new Lean metric they call Overall Task Effectiveness which is designed to identify hidden losses by defining target task times. This helps to establish time standards and identify causes of waste that are not easily identifiable in manual assembly lines (Braglia et al. 2019: 419). Frazee and Standridge compared the application of the constant work in process (CONWIP) and Paired-Cell Overlapping Loops of Cards with Authorisation (POLCA) manufacturing control

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systems in a high-mix-low-volume batch processing environment with a view to controlling work in process (WIP) measured in terms of lead time, maximum work in process, and throughput. They observed that CONWIP is superior in controlling work in process throughput at a lower level of work in process than POLCA, while lead times are the same. At higher levels of work in process the performance of CONWIP and POLCA become equivalent in terms of lead time and throughput (Frazee & Standridge 2016: 447). Girod et al. suggest the use of a hybrid-dynamic manufacturing system, where an express production line is introduced for relatively high demand products with shorter cycles and a standard line is maintained for all other products. This leads to shorter overall lead times for the high demand products supporting the overall lean goal of customer value creation (Girod et al 2014: 2585-2586, 2591). Kishimoto et al. performed Value Stream Mapping on a make-to-order company and then applied Lean tools such as 5s for the preparation phase to allow better Lean understanding. They then implemented production levelling and CONWIP on the basis of Kanban cards leading to substantial improvement of on-time delivery performance (Kishimoto et al. 2019: 955, 957). Kjersem et al. have successfully applied pull production concepts, in particular Kanban, takt time and CONWIP, in the shipbuilding industry to reduce work in process on the line. They maintain that continuous flow can be achieved for repetitive processes even if the parts vary (Kjersem et al. 2014: 254). Matt (2009) looked at material handling systems in a make-to-order setting with a large variety of product types and a high variability in demand with a view to reducing the production lead time. He proposed the introduction of the use of axiomatic design – an approach to "develop a scientific, generalized, codified, and systematic procedure for design" (Matt 2009: 152) – to make manufacturing support systems leaner. Applying axiomatic design in a make-to-order context, he identified three functional requirements for material handling systems that can be implemented in operations: minimization of the distance between source and process, provision of complete order picking and elimination of unnecessary motion, and prevention of defects throughout the material handling operation (Matt 2009: 153, 156). Messner et al. propose to create a closed-loop information system to automatically update planning parameters based on fast changing historical data related to process and products in a high-mix-low-volume setting. Using a data platform to update shop floor data in a closed loop process, can assist to improve master data in the Enterprise Resource Planning system as it is collected in a contextual format (Messner et al., 2019: 694). This can support the concept of mass customisation approaches in an increasingly integrated environment

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fitting into the Industry 4.0 concept. Metternich et al. have identified volume and product mix flexibility as the most commonly required types of flexibility and have developed a model for production planning taking product variability and total capacity demand into account (Metternich et al. 2013: 83). Powell suggests to use Kanban boards as an effective visualisation tool to control production by limiting work in process through application of CONWIP and strict control of Kanban cards. In this context, daily production scrums are a critical success factor for lead time reduction (Powell 2018: 143). Slomp et al. propose a lean production control system that is based on a pull system and integrates production levelling, CONWIP, First-In-First-Out (FIFO) and takt time to improve on-time delivery and reduce flow times (Slomp et al.: 2009: 594). Svacara and Kralova examined the use of heuristic production scheduling algorithms balancing the machine assignments with production order families, optimising high-mix-low-volume flow shop manufacturing systems (Svacara & Kralova 2012: 150). Thürer et al. advocate a workload control concept that is able to regulate lead times, capacity and work in process by combining continuous with periodic order releases. This allows the release of work orders between periodic release when work centres are starving, consequently improving tardiness and throughput results (Thürer et al. 2012: 951-952).

Layout design plays a special role within high-mix-low-volume manufacturing literature, as the material and production flow within the plant have a particular relevance in avoiding waste. Arasanipalai Raghavan et al. have used a Value Stream Mapping approach to identify shop floor inefficiencies in a high-mix-low-volume operation. They have employed Lean methods such as a Kanban-based pull system, and an optimised straight-line material flow layout with an incorporated cell-manufacturing approach on a pilot line. This has substantially reduced cycle time, lessened work in process in the line and lowered overall space requirements (Arasanipalai Raghavan et al. 2014: 347, 357). Horbal et al. have looked at the implementation of a set of lean tools and their impact on shop floor performance. They observed that, when Lean tools such as one-piece-flow, standardised work, material presentation, milk run deliveries and a pull system were suitably modified, it improved productivity by a third and practically halved the space requirement (Horbal et al. 2008: 259, 266). Hussain et al. have employed the Value Stream Mapping approach to identify processes with high cycle-time and long changeover times and suggest to modify the single-piece-flow operation by adding a supermarket approach (Hussain et al. 2020: 841-842). Irani and Huang suggest a network of 'layout modules'

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to better suit a multi-product facility. A mix of layout approaches are modularised in a hybrid fashion to allow for increased flexibility in facility design. Modules are based on material flow networks, machine groupings, and flow pattern characteristics and can encompass the following types: flowline, branched flowline, cell, machining centre, functional layout and patterned flow (Irani & Huang 2000: pp. 261-262). Kauralova and Shvetshenko examined the implementation of the facility layout into work cells and the evaluation of line levelling to improve flexibility in a high-mix-low-volume operation. It is designed to enable quick changes in the production schedule and product design. The research showed an optimised time distribution for work cells with a reduction of tools required on the line (Kauralova & Shvetshenko 2015: 91, 98)

As the high-mix-low-volume requirements necessitate different process flows to allow for more flexibility, some scholars have put their attention to evaluating processes to allow for optimisation. Cannas et al. propose to start the production planning and control process from the project requirement phase, i.e. before the design phase and therefore before the decoupling point, and then to add Lean tools such as Asaichi (meaning morning markets on the shop floor, as a way to manage problem solving), continuous improvement and visual control in order to improve planning performance, flexibility and consequently delivery performance (Cannas et al. 2018: 138-139). Hong et al. examine the possibility of concurrent product design and process planning. They have applied an AND/OR tree for modelling design configuration variations, where each node in the tree is correlated with manufacturing parameters. Using programming and numerical optimisation, optimal design configuration parameters and manufacturing process parameters are matched. (Hong et al.: 6354-6355, 6364). Iakymenko et al. evaluate the research into engineering change management. They emphasise the inevitability of engineering changes, as well as the need for engineer-to-order companies to accommodate them, as they add value to the customer offer. However, they also create inefficiencies and therefore waste, such as rework, scrap, delays and longer lead times. The decoupling point is the suitable break-off point for an engineering freeze. They highlight the need for further research into engineering change management practices (Iakymenko et al. 2018: 149-150).

One important area of research into high-mix-low-volume manufacturing is the utilisation of Lean bundles. This approach looks at the effect of the use of numerous Lean tools 'bundled' together. Researchers have approached this from identifying one or two bundles and evaluating these in-depth, or by taking a holistic view where

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all parts are combined together to form a broader Lean philosophy. Birkie & Trucco identified eight Lean practice bundles that have numerous Lean tools associated with them. They examined how complexity and dynamism affect the implementation of Lean bundles and the operation performance in an engineer-to-order context. They found that there is little evidence that any of the Lean bundles cannot be implemented in an engineer-to-order setting due to complexity and dynamism. In fact, complexity appears to encourage the implementation of Lean concepts. However, dynamism poses challenges to the implementation of Lean leading to possible setbacks. Both dynamism and complexity appear to confirm the positive link between Lean and performance. Practitioners are advised to bear in mind the differences in context of implementation and allow for adjustments in order to benefit from Lean concepts (Birkie & Trucco 2016: 355-356). Birkie et al. investigated the impact of Lean bundles, spanning both shop floor and transactional processes, on sustained performance improvements. They observed that engineer-to-order operations use similar sets of Lean practices in predefined bundles as repetitive operations. However, customisation of practices has been perceived to fit the more dynamic and complex setting. Performance sustenance is reinforced by more integrative Lean practice implementation across both the shop floor and the transactional process (Birkie et al. 2017: 472-473). Marin-Garcia and Carneiro examined the implementation of Lean bundles with 81 subsets in Spanish companies operating in alternative fields to mass production. It emerged that tidiness and cleanliness practices, quality improvements, staff involvement, continuous improvement, customer relationship management, standardization of processes, cell manufacturing and supplier relationship management were frequently reported to have been implemented. However, use of pull systems, Value Stream Mapping, Just-In-Time/Kanban, Single Minute Exchange of Die (SMED), automation, design integrated with manufacturing and knowledge management were not commonly perceived (Marin-Garcia & Carneiro 2010: 271). Pandian et al. introduced a combined approach of a zero-defect-out strategy, a cellular production layout and employee involvement in a high-mix-low-volume operation. The company aimed to reduce excessive work in process, prioritisation conflicts and transportation bottlenecks, while improving employee performance on productivity, responsibility, accountability, creativity and change management. The Lean implementation resulted in tangible improvements in scrap rate, lead time, on-time delivery and cost saving Pandian et al. 2010, 1, 6). Powell et al. have evaluated a new set of ten Lean principles that are designed for an uncertain environment such as engineer-to-order. Particular attention is given to the avoidance of waste defined

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as “anything that incurs a cost of any kind, the elimination of which does not reduce the value delivered” (Powell et al. 2014: 572). Emphasis is put on Lean principles that additrionally highlight stakeholder value, stakeholder systems integration, transparency, modularisation and technology (Powell et al. 2014: 574). Sahoo and Yadav have evaluated the introduction of two Lean bundles, Total Quality Management (TQM) and Total Productive Maintenance (TPM), as standalone approaches as well as concurrently. While on a standalone level both bundles improve long term performance such as financial, manufacturing and workplace performance, concurrent implementation maximises the business performance (Sahoo & Yadav 2017: 392-393). Shah and Ward (2003) recommend four Lean bundles – just-in-time, total quality management, total preventive maintenance and human resource management – and examine their effects on operational performance in plants with various ages, sizes and levels of unionisation. They observed that Lean practice implementation is positively correlated with plant size, while age and unionisation have less of an impact than may be expected. Lean practices have been proven to have a beneficial effect on operational performance. But a concurrent implementation of bundles has a synergistic effect on manufacturing performance (Shah & Ward 2003: 145-146). In a later research paper, Shah & Ward (2007) examine the evolution of Lean practices to identify their interrelations. They argue that each Lean component is necessary but not sufficient to constitute the system. A conceptual definition incorporating both internal as well as external components is proposed, highlighting the integrated nature of Lean manufacturing with ten positively correlated dimensions of Lean identified (Shah & Ward 2007: 799-801). Simmons et al. have explored the effect of the introduction of basic Lean tools such as 5s, standardised work, line balancing, visual controls, point of use storage and quality at source in a small, low volume enterprise setting. They observed a dramatic increase in throughput, a considerable decrease in defects, and a general improvement in the overall efficiency of the manufacturing processes. However, they emphasise that an organisational buy-in from all staff levels must exist (Simmons et al. 2010: 5).

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Tomašević et al. (2020)	In most studies a narrow set of tools is applied with little consideration to their suitability in high-mix-low-volume environments
Adlin et al. (2020)	Lean tools are applicable in a high-mix-low-volume setting, but are customised to become more suitable
Shah and Ward (2007)	Lean production is approached from either a philosophical and holistic aspect, or from a tools- and technique-based aspect
2. Environment	
Holweg (2005)	Volume, product, and process allow responsiveness to customer orders; but given multiple contingency factors, no one generalisable concept to order fulfilment fitting all, can be found
Azadegan et al. (2013)	Lean approaches mitigate the challenges of complex and dynamic environments
Bortolotti et al. (2015)	Soft practices are more pervasive in high performance Lean plants, while hard practices are essential but not differentiating factors
3. Value Stream Mapping	
Strandhagen et al. (2015)	Adapted Value Stream Mapping can identify sources of waste affecting lead time in an engineer-to-order operation; sources of waste exist in particular in non-physical processes such as sales, engineering and project management
Seth et al. (2017)	Value Stream Mapping does not differ fundamentally in simple or complex environments; guidelines assist application
Matt (2014)	Adapted Value Stream Mapping can be applied in an engineer-to-order operation taking into consideration the synchronization points ahead of merge activities and the separation of customer orders into appropriate manufacturing orders
4. Shop Floor	
4.1. Production Control	
Becker et al. (2015)	Machining equipment effectiveness (MEE) was designed as a new overall equipment efficiency (OEE) measure to better account for the variations that define the high-mix-low-volume operation
Bohnen et al. (2013)	Product clustering to allow for distinct levelling patterns to allow family-specific production runs
Bortolotti et al. (2013)	Customisation does not reduce the link between Just-In-Time and a company's performance, both in terms of efficiency and responsiveness; demand variability does reduce the impact of Just-In-Time on responsiveness but does not necessarily adversely affect efficiency
Braglia et al. (2019)	Introduction of new metric for Lean to identify hidden losses by defining standard task times
Frazee & Standridge (2016)	Work in Process manufacturing control techniques CONWIP and POLCA are compared to show that at lower maximum work in process, CONWIP is superior in terms of throughput

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Girod et al. (2014)	Separation of production line into an express line and a standard line to reduce lead time for high demand products with shorter cycles leading to reduced lead times
Kishimoto et al. (2019)	Value Stream Mapping is complemented with the introduction of Lean tools such as 5s, production levelling and CONWIP with Kanban cards leading to a substantial improvement in on-time delivery
Kjersem et al. (2014)	Successful application of pull production concepts (Kanban, takt time & CONWIP) within the shipbuilding industry to reduce the work in process on the line
Matt (2009)	Use of axiomatic design to make production support systems, such as material handling systems, leaner to reduce production lead times
Messner et al. (2019)	Collecting contextual closed-loop data relating to product and process directly from machines can improve data quality including master data in the Enterprise Resource Planning (ERP) System
Metternich et al. (2013)	Identification of product mix and volume as the most commonly required types of flexibility; production planning model devised for product variability
Powell (2018)	Using Kanban boards, CONWIP and Kanban cards in combination with production scrum, can be an effective way to reduce lead times in ETO setting
Slomp et al. (2009)	Introduction of production control systems based on lean concepts such as production levelling, First-In-First-Out, CONWIP, and takt time to improve on time delivery and reduce flow times
Svacara & Kralova (2012)	Use of heuristic production scheduling algorithms balance machine assignments with production order families, optimising high-mix-low-volume flow shop manufacturing systems
Thürer et al. (2012)	Workload control concept regulating lead times, capacity and work in process by combining continuous with periodic order releases; release of work orders between periodic release when work centres are starving improves tardiness and throughput results
4.2. Layout	
Arasanipalai Raghavan et al. (2014)	Implementation of Lean methods such as Kanban-based pull system, and an optimised straight-line material flow layout with an incorporated cell-manufacturing approach improving cycle time, space requirements, and reducing work in process on the line
Horbal et al. (20018)	Identification of modified shop floor Lean tools to improve productivity and reduce space requirements
Hussain et al. (2020)	Use of Value Stream Mapping to identify bottlenecks and modify a single-piece-flow operation to add a supermarket within the line
Irani & Huang (2000)	Modularisation of hybrid facility layout patterns to allow increased flexibility in a multiproduct facility
Kauralova & Shvetshenko (2015)	Application of work cell concepts to support higher production flexibility and faster product changeovers leading to optimised time distribution

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4.3 Process	
Cannas et al. (2018)	Starting the production planning and control process at the project requirement phase, combined with Lean tools such as Asaichi, continuous improvement and visual control to improve planning performance, flexibility and consequently delivery performance
Hong et al. (2010)	Concurrent product and process design using an AND/OR tree model and programming to match the optimal product design and process parameters
Iakymenko et al. (2018)	Engineering change management is necessary as a it adds value to the customer; however, it also creates waste in the form of scrap, rework, delays and longer lead times; implementing a design freeze at the decoupling point can mitigate some of the waste
5. Bundles	
Birkie & Trucco (2016)	Complexity and dynamism do not pose an obstacle to the implementation of Lean bundles in engineer-to-order contexts; complexity encourages the implementation of Lean concepts, while dynamism poses challenges; complexity and dynamism appear to confirm the positive link between performance and Lean
Birkie et al. (2017)	Engineer-to-order operations employ similar sets of Lean practice bundles as repetitive operations; but there is need for customisation; performance sustenance is reinforced by more integrative Lean practice across shop floor and transactional processes
Marin-Garcia & Carneiro (2010)	Implementation of Lean bundles with 81 subsets in Spanish companies operating in alternative fields to mass production, where tidiness and cleanliness practices, quality improvements, staff involvement, continuous improvement, customer relationship management, standardization of processes, cell manufacturing and supplier relationship management were frequently reported; use of pull systems, Value Stream Mapping, JIT/Kanban, Single Minute Exchange of Die (SMED), automation, design integrated with manufacturing and knowledge management were infrequent
Pandian et al. (2010)	Introduction of a combined approach of a zero-defect-out strategy, a cellular production layout and employee involvement in a high-mix-low-volume operation led to improved scrap rate, on-time delivery, cost savings and lead time
Powell et al. (2014)	Development of ten new Lean principles to account for the more uncertain engineer-to-order context; there is an emphasis on value creation for stakeholders and modularisation
Sahoo & Yadav (2017)	Evaluation of Total Quality Management and Total Productive Maintenance as standalone approaches improved performance, while their concurrent introduction maximised long term business performance
Shah & Ward (2003)	Lean practices of total quality management, human resource management, total productive maintenance and just-in-time have a beneficial effect on operational performance; concurrent implementation of bundles has a synergistic effect on manufacturing performance

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Shah & Ward (2007)	A conceptual definition incorporating both internal as well as external components is proposed highlighting the integrated nature of Lean manufacturing with ten positively correlated dimensions of Lean identified
Simmons et al. (2010)	Introduction of basic Lean tools such as 5s, standardised work, line balancing, visual controls, point of use storage and quality at source led to a dramatic increase in throughput, a considerable decrease in defects; organisational buy-in from all staff levels is imperative

Figure 8: Table of Selected Literature

3.2.3. Lean Bundles and their Relevance in an Engineer-to-Order Application

Shah and Ward (2003) define bundles in Lean production as "interrelated and internally consistent practices" (Shah & Ward 2003: 129). Often Lean manufacturing is approached from evaluating one particular tool or one specific bundle. Much of the literature and research focuses on Lean practices or Lean tools and their relevance to the shop floor. While Lean shop floor tools are essential to Lean improvement for a manufacturing firm, Bortolotti et al. (2015) have found them not to be differentiating factors. Increasingly, therefore, scholars have looked at a more holistic approach to evaluate the relevance of Lean methodology. Some authors maintain that in order to reap the best operational results, Lean must be approached as a philosophy (Shah & Ward 2007; Powell et al. 2014: 572, Seth et al. 2017: 404). Returning to the source of Lean manufacturing, i.e. is the Toyota Production System, it is evident that it was intended to be applied as a whole system. The house of Lean (Figure 7) incorporates many individual parts that are combined into one integrative whole that works as a system. It should therefore hardly be surprising that applying Lean as a philosophy leads to better performance results than implementing only selected component parts.

The packaging of Lean practices into logically connected, coherent bundles helps to structure Lean practices and assists in analysing their impact on modern manufacturing entities. Birkie et al. suggest to implement Lean both on the shop floor as well as across other transactional business practices (Birkie et al. 2017: 460). Transactional processes are processes that are not involved in shop floor activities but are involved in the communication and interactions between different entities internal or external to the company that may have a bearing on the shop floor.

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	Hard	Soft
Internal	**Total Quality Management & Visual Management** **Just-in-time / Flow** **Total Productive Maintenance** **Standardisation**	**Human Resource Management**
External	**Lean Purchasing (LP)**	**Supplier Involvement & Development** **Customer Involvement and Partnership(CIP)**

Figure 9: Lean Bundles in Relation to Hard & Soft Practices and Internal & External Process

For this study the bundles suggested in the study by Birkie and Trucco (2016) will be applied to the case analysis as it takes the widest approach to Lean methodology, while providing a structured perspective to Lean bundles. It acknowledges the need for approaching Lean as a philosophy, lived by the whole organisation, to have the largest possible impact. This also finds expression in the *hoshin kanri* approach where the goal becomes the strategy which the whole company aspires to. Synergies can only arise when the practice bundles are employed together. Furthermore, it acknowledges the two perspectives of internal and external business processes, where the internal focuses on activities within the organisation, while the external focuses on relationships with outside stakeholders such as suppliers and customer. The Lean bundles are structured to fit the manufacturing set up. Moreover, the approach has taken into consideration the particularities of a high-mix-low-volume, engineer-to-order environment. To complement the approach, the research paper of Birkie et al. will be considered as it also considers the relevance of soft (aspects relating to people) and hard (aspects that are of a technical or procedural nature) factors impacting the results of Lean methodology (Figure 9). It also acknowledges the need for a long-term approach, where sustenance and extensiveness of implementation are taken into consideration. Sustenance is supported by an integrative approach to Lean bundles. Additionally, it identifies the need of engineer-to-order companies to customise the Lean tools they employ or to complement them with additional suitable tools.

Figure 10 provides an overview of relevant Lean bundles and their Lean practices. Indicators for performance improvement in the Lean understanding of elimination of waste include the following:

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- Lead time reduction
- Reduction in takt and cycle time
- Improvement in on-time delivery
- Improvement in supplier on-time delivery
- Productivity increase
- Financial savings
- Reduced scrap rate and reduced total cost of poor quality
- Safety improvements
- Improvements in the material on-time delivery

Lean Practice Bundle	Practices as Suggested by Birkie & Trucco (2016)	Additional Practices
Total Quality Management and Visual Management – continuously improve and sustain quality	Competitive benchmarking Quality management programmes Total quality management Process capability measurements Formal continuous improvement programme	5s Poka Yoke Kaizen circles
Just-in-time / Flow – flow and continuously removing waste	Lot size reductions JIT/continuous flow production Pull system/Kanban Cellular manufacturing Cycle time reductions Focused factory production systems Agile manufacturing strategies Quick changeover techniques Bottleneck/constraint removal Reengineered production processes	Takt time reduction Cycle time reduction Throughput reduction Cellular layout Kitting CONWIP Process improvements Value Stream Mapping Planning & scheduling strategies Process capability measurements Transportation reduction Reduction in excessive movement First pass yield (FPY) Benchmarking
Human Resource Management – building the human resources as per needs of lean implementation)	Self-directed work teams Flexible, cross-functional workforce	Lean teams Gemba walks *Asaichi* (morning markets on the shop floor) Multi-functional teams Job rotation

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Total Productive Maintenance – maximisation of equipment effectiveness	Predictive or preventive maintenance Maintenance optimization Safety improvement programmes Planning and scheduling strategies New process equipment or technologies	Overall Equipment Efficiency Single Minute Exchange of Dies, quick changeover techniques Process capability measurement Separation of daily maintenance from strategic maintenance
Standardisation (STD)	Standardising processes and procedures	Modularisation Product families by size Written procedures
Lean purchasing (LP)	Reduced purchase order sizes Short order placement processes Reduced need for incoming material inspection	Long-term purchasing commitments Kanban boxes for common parts Kanban for replenishing
Supplier involvement & development (SID)	Close contact and long-term relationship Supplier development and certification Improvement commitments from suppliers	Supplier feedback Supplier audits & certification Lead time improvements Quality improvement commitments
Customer involvement and partnership (CIP)	Customers' direct engagement in product offerings Customers' feedback on different performances	

Figure 10: Lean Bundles (adapted from Birkie & Trucco 2016: 346)

Visual management helps to make issues observable and forces an organisation to analyse their setup. Total quality management then puts this in context, defining where waste and overburdening exists. It assists in putting this into a structure that allows for sustaining results and visualising when there is slippage.

A just-in-time approach forces a company to improve their overall organisation by reducing what is not necessary from the process to allow for a flow of production. Analysing what stops the flow, e.g. bottleneck removal, helps to reduce overburdening elements from the system.

Human resources management focuses an organisation to have the members of an organisation on board. It is necessary to hear all voices reflecting all functions in order to truly remove waste and to sustain this process. It also ensures that the burden is spread, and overburdening individual team members can be identified.

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Total productive maintenance ensures the smooth flow of production. This means that stoppages don't cause waiting time or that overburdening machines does not lead to a reduction in flow.

In an effort to improve process flow standardisation, reduction of variation is important. Clearly in a high-mix-low-volume setup this has to be done in a measured and meaningful way.

Equally, for Lean purchasing, a measured approach is necessary as quantities are directly linked to specific customer orders. To reduce waste more meaningfully, close communication with suppliers is more useful. Consolidated shipments are an effective way to reduce waste.

Reducing waste (*muda*), improving flow (*mura*) and decreasing overburdening (*muri*) supports the goal of offering value to the customer. In an engineer-to-order setting, this also means that close communication with the customer at the outset helps to ensure that flow is possible and that the processes can be geared to supplying the specific customer order.

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4. Case Study

4.1. Company Overview

Company A, the company under review for this case study, is a subsidiary of a multinational group of companies headquartered in Europe. The Group of Companies employed 5000 staff and had a turnover of EUR900 million at the time in question for this study. It operated 65 entities globally, of which 40 were production sites. Company A was the largest manufacturing plant within the Group. Within one operation, the plant produced half of the complete product portfolio of the entire Group. The company employed 400 staff with an annual turnover of EUR60 million. The plant ran 11 production lines on 40,000 square metres.

The Group of Companies had recently been purchased by a private equity company and was undergoing major change. Company A had undergone two major layoff activities of 150 employees each over the period of two years. Company A had been unprofitable for a couple of years and a major restructuring programme was initiated to bring about a turnaround. At that point the actual on-time delivery rate for the plant was around 30% across the product portfolio.

The company operates in an engineer-to-order environment, where products are highly engineered and where the bill of materials changes with every order. Consequently, the order penetration point or customer order decoupling point is generally at the design stage of the products. The lot sizes per customer vary from one unit to a maximum of 50 units with an average monthly output of 1500 units distributed over 400 monthly orders. The company has a customer base of 1000 global customers and a supplier base of 300 active suppliers. Customer relationships are often complex, where many stakeholders are involved and specific suppliers are regularly stipulated by customers. Many products require certification and approvals by third party auditors before shipment, where customers frequently request to participate in certification audits.

Due to the poor performance of the Group of Companies in general and Company A in particular, a restructuring programme with a Lean focus was initiated. Within Company A the programme was implemented over a span of two years. There was

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a high sense of urgency due to the poor performance and the dissatisfaction of customers, suppliers, staff and, naturally, headquarter.

4.2. Company Environment

Company A operates in an environment defined by a very high level of uncertainty. Due to the large number of customers (Figure 11), demand varies considerably, and consequently capacity planning is complex. As the company operates in a typical engineer-to-order environment with a very high mix of products, the production is not based on forecasts but on confirmed customer orders. A very high frequency of engineering changes and customer-initiated delivery delay requests, make planning very challenging. The high level of customisation required by customers is also reflected in the unusually high level of white collar workers in proportion to blue collar workers, where 50% of staff are white collar workers.

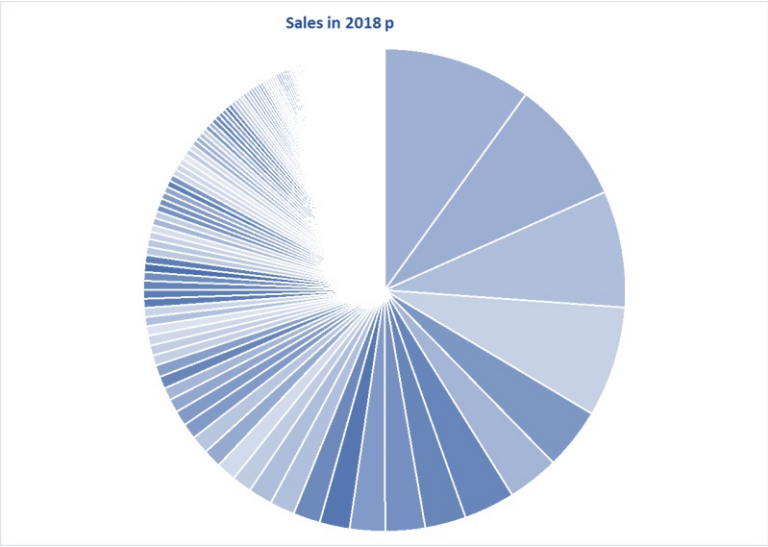

Figure 11: Sales per Customer Within a Given Year with a Total of 400 Customers

The company produces for four business units that are separated according to the technical requirements of customer groups, applications, and markets. Production lines in Company A are divided according to product lines and production processes, as well as widely varying size and weight of each product (Figure 12). All products require engineering input and have some level of customisation.

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Business Unit	Production Line	Market/ Application	Lot Sizes / Customer	Production	Process Type
Business Unit I	Product 1 Product 2	Food & Beverages, Chemical Industry HVAC, Food & Beverages, Oil & Gas, Chemical, Refrigeration, Marine	1-10 units 1-50 units	Manual assembly of each unit with high level of customisation Serial production with customisation pre-brazing process	Manual Assembly Batch Production
Business Unit II	Product 3 Product 4	Marine, Railway Marine, Railway	1-10 units 1-50 units	Completely engineered with high level of manufacturing content Completely engineered with high level of manufacturing content	Line & Cellular Production Line Production
Business Unit III	Product 5 Product 6 Product 7	Industrial HVAC, Data Centres Slaughter Houses, Cold Storage Supermarkets, Cold Storage	1-5 units 1-30 units 1-50 units	Completely engineered with numerous production process Highly engineered with numerous production process, seasonal demand pattern Customised with >100 modules & numerous production processes, seasonal demand pattern	Line Production Line Production in Batches Line Production with One-Piece-Flow aspects
Business Unit IV	Product 8 Product 9 Product 10	Power, Oil & Gas Power, Industry Railway	1-5 units 1-5 units 1-10 units	Completely engineered with numerous production steps Completely engineered with numerous production steps & high manual assembly content Slightly customised with a technical assembly	Line Production Batch Production Cellular Production
Project Engineered Solutions	Product 11	Paper & Chemical Industry	1-10 units	Completely engineered with numerous production processes & a high manual labour content (manual welding)	Batch Production

Figure 12: Product Portfolio and Production Lines

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On one hand, the company produces a large array of products with a high level of customisation and engineering, but individually modest numbers. On the other hand, the overall quantities produced are substantial and require a lot of space as most of the products are large in size as well as heavy. Figure 14 provides indicative statistics on the total volume of the operation, while Figure 13 provides an idea of the individual product characteristics relevant to the operation. With the exception of Product Group 2 all products require cranes to be transported. Consequently, so do some of the parts required to manufacture the final product. That means that safety is an ongoing concern.

Product	Production Characteristics	Average Size & Weight	Annual Quantity	Monthly Average Quantity
Product Group 1	Highly customised; small steady volume of large amount of variants	500-2000kg 0.2m^3 – 5m^3	720	60
Product Group 2	Serial production; steady volume of numerous but limited variants	0.1-0.5 kg 0.01m^3 – 0.1m^3	1,740	145
Product Group 3	Highly engineered, sizable volume, unsteady, varying demand	100-300kg 0.5-1.0m^3	3,600	300
Product Group 4	Highly engineered, large products, unsteady & varying demand	200-800kg 1.0-4.0m^3	420	35
Product Group 5	Small volume of highly engineered, very large & heavy products with very high-quality requirements (e.g. nuclear power stations)	3-5t 50-150m^3	300	25
Product Group 6	Batch production of large, highly engineered products	300kg-800t 3-10m^3	2,100	175
Product Group 7	Batch production in a one-piece flow environment	50-200kg 0.5-2m^3	7,200	600
Product Group 8	Small volume of engineered, large products produced in batch	100-500kg 1-5m^3	600	50
Product Group 9	Small volume of engineered, large products produced piece by piece	100-500kg 2-10m^3	600	50
Product Group 10	Steady volume of products assembled in cell format	50kg 0.1m^3	600	50
Product Group 11	Small volume of engineered, products produced in batch	100-500kg 1-5m^3	300	25
Total			**18,180**	**1,515**

Figure 13: Product & Production Characteristics

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Factory Statistics	
Annual Welding Seam	150,000 metres
Annual Consumption of Screws	300,000 pieces
Annual Consumption of Tubes	1,700,000 metres
Annual Consumption of Metal	3,000 tonnes
Average Working Hours Required for the Production of One Heat Exchanger	30 hours

Figure 14: Significant Annual Factory Statistics

4.3. Lean Approaches Implemented

4.3.1. Status Quo and Lean Restructuring Programme

In the past, Company A had experienced a very high level of demand and very little competition. This allowed the company to operate in a very comfortable and well-resourced environment. However, the increasingly competitive situation and the decreasing demand made it necessary for the company to raise their level of efficiency. As these adjustments are painful and accompanied by employee resistance, the process was started haphazardly and with an initial lack of commitment.

Company A started a Lean restructuring programme to regain control over its operation and improve on key performance indicators (KPIs) that were measured across all sister sites such as profitability, customer on-time delivery, overall cost of poor quality (COPQ) and lost time injury frequency rate (LITFR). Benchmarking against sister sites, the company scored in the lowest quarter. As the actual on-time delivery was as low as 30%, the starting point naturally had to be the improvement of achieving the committed delivery dates to the customer. Expectedly, the lack of reliability led to severe dissatisfaction on the part of customers.

But as the Lean bundles approach shows, improvement activities are connected, and the approach had to be integrative. The poor delivery performance was related to poor performance across functions and stakeholders. The overall supplier on-time delivery was very low. The shop floor team was disorganised and unmotivated due to the recurrent layoffs. The production planning was patchy, and there was a lack of

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clear visibility of priorities. The project management team was busy with placating the customer rather than focusing on expediting and coordinating orders. The layoffs had been poorly thought-through, leaving some production lines severely understaffed, while effectively dissolving the maintenance team. In consequence, the 90 critical machines were not appropriately taken care of and spare parts were missing, leading to more delays. Furthermore, the warehouse and the painting function, while still on the premises, had been outsourced to external parties. Due to the very high mix of products as well as the very high level of customisation and engineering, the complexity of the parts is also very high. This makes it nearly impossible for external parties, unfamiliar with the products, to link the parts to the ongoing projects. This made it very hard for the quality team to control the quality within the production lines as well as the quality of final goods leaving the plant. This was compounded by constant delivery order change requests at all stages of projects initiated by customers. As there was no contractual penalty for lack of a commitment on the part of the customer, this was a regular occurrence and even multiple reoccurrence. The engineering department struggled to keep up with the constant changes of ongoing orders leading to a lack of committed orders to suppliers.

While flexibility is priced in an engineer-to-order environment, the prevailing level of uncertainty led to an unsustainable level of waste. The lack of planning and organisation caused a lack of visibility, while the sense of urgency towards to customer meant that faster but less efficient solutions had to be accepted.

The following ***muda*** or categories of waste were inevitable:

- **Overproduction** – due to the constantly changing customer order requests, parts and final goods were produced, which were later unwanted
- **Waiting** – waiting for machine repairs due to a decimated maintenance team and a lack of required spare parts; waiting for parts as they could not be found in the warehouse or were not yet delivered by the supplier; waiting to find the right tools as there was scant 5s on the shop floor; waiting for finished goods to be packaged as the production was late; waiting for delivery as the logistics companies could not be booked in time
- **Transportation** – due to the poor organisation on the shop floor, and poorly thought-through production lines as well as due to the lack of timely order of parts, transportation of items within the plant was a key element of waste

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- **Excessive processing** – a lack of a clear understanding of customer requirements and occasionally the need to placate customers, made excessive processing or the provision of better quality than required an additional source of waste
- **Inventory** – required inventory was often missing, while obsolete inventory was cluttering the warehouse as well as the shop floor
- **Excessive motion** – badly organised work processes and work stations regularly made excessive motion necessary; poorly managed parts within the warehouse required searching, which also caused additional need for motion
- **Defects** – repairs were regularly required as the overall lack of organisation and visibility caused mistakes and poor quality; rework was regularly required, either because parts had a design fault, or because suppliers delivered poor quality, or because parts were internally badly made, or because machines were defective; where rework was impossible parts were scrapped; material recalls required suppliers to rework parts or reproduce parts; worst of all, due to defective products, numerous customer claims caused expensive repairs or complete reproduction and painful damage to the company reputation
- **Human talent** – inevitably employees were busy with placating customers and solving problems across all functions

Due to the dire situation of the company, swiftness to remedy the situation was imperative. The Lean restructuring implementation was started involving all departments and functions and was quickly ramped up as illustrated in Figure 15. The starting point was identifying priorities that would yield the largest benefits for performance improvement in the shortest possible time. To build up critical mass in the ramp up of the Lean restructuring programme, the support of the team on all levels was vital.

Company A had the following functions and departments:

- **Human Resources Management** – in charge of recruiting, personnel management (including payroll, disciplinary functions, promotions, demotions, performance appraisals) , training, internal communication, staff activities, staff transportation, canteen
- **Design & Engineering** – in charge of process engineering including routing, design and engineering for all product lines including knowledge transfer with sister sites and communication with the customer on a technical level

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- **Supply Chain Management** – in charge of supplier management, order management to the suppliers, on-time delivery of all required parts, supplier development and supplier relations, internal logistics and warehouse, external logistics, exports, imports and customs clearance
- **Project Management & Order Execution** – in charge of timing, coordination and execution of customer orders, and production scheduling, material planning, communication with the customer on delivery changes, scheduling of audit and certification requirements (classification for the marine market)
- **Production** – in charge of production lines, on-time completion of all products, management of production processes, machining, brazing, sheet metal production, welding, painting and total productive maintenance
- **Quality** – in charge of incoming and outgoing quality inspection, management of the quality system, recertification of all required licences including ISO9000 and ISO14001, communication with classification bodies in the marine sector and other auditing entities, safety, health and environment (SHE) function, claim management, supplier audits
- **Finance** – bookkeeping, monthly financial reporting, budgeting, treasury, controlling, management accounting

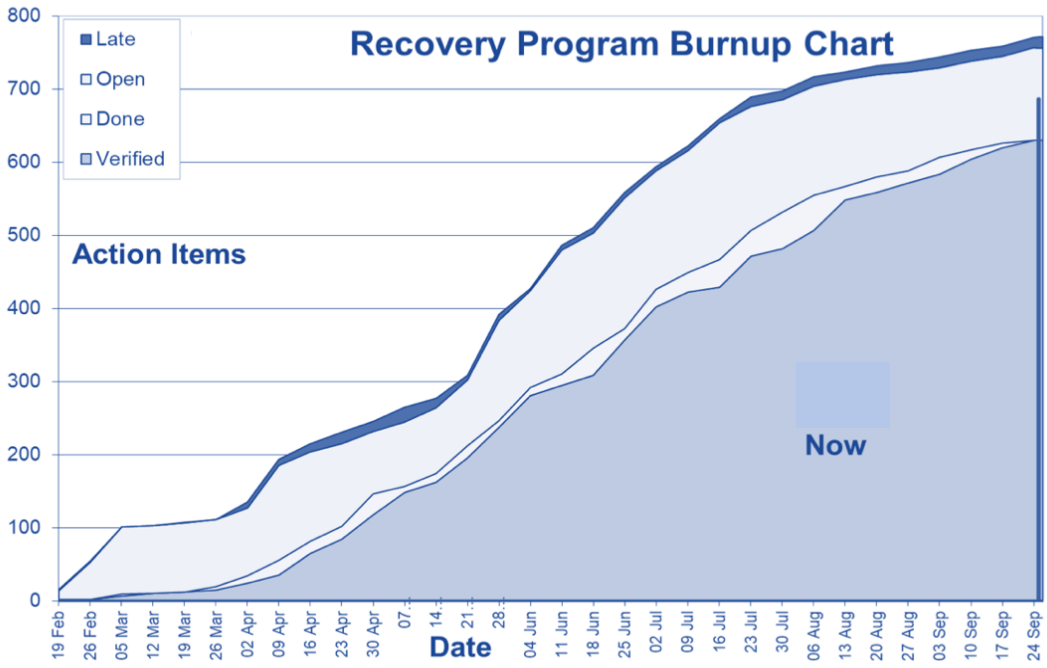

Figure 15: Restructuring Programme Actions Development

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At the outset, all managerial functions had to be roped in to the Lean restructuring programme and convinced of its necessity. While it would clearly be disruptive, it would also lead to benefits for their teams as well as their departmental functions. In a second step, the need for a Lean restructuring programme had to be communicated into the next level of the organisation. And finally, the staff working on the shop floor had to buy into the inevitable need for change.

4.3.2. Human Resources Management Department

In order for a restructuring approach based on the implementation of Lean concepts to gain ground, it is imperative to have the staff across all functions and on all levels onboard. Consequently, any Lean approach has to start from the involvement and eventual conviction of the meaningfulness and usefulness of Lean concepts for all levels of staff and for each individual employee. It is imperative that Lean can be sustained, and is not perceived to be only one more management programme that emerges only to disappear after a brief time when the new fad is over.

After the buy-in of the management team, i.e. the heads of department, the best starting point for a coherent communication strategy was the Human Resources Management Department to ensure an integrative approach as well as coherence of message.

At the outset, the critical human resources that were missing due to the earlier layoffs had to be defined and then recruited. For the first wave of recruitment within a period of three months, a total of 80 new staff had to be found and engaged. This was an exceptional challenge for the Human Resources Management Department as well as for the other members of staff, as there was an addition of 30% of new staff members that needed to be trained and integrated into the existing team (Figure 16). However, it was also an opportunity to bring new thinking and a breath of fresh air into the company, where the new members of staff had no historical burden. The second wave of recruitment was more gradual over a longer period of time adding another 50 members of staff to the existing team over a period of 8 months. While a substantial number of new recruits were required on the shop floor and the Maintenance Department needed to be set up again, there also were additions in all other departments.

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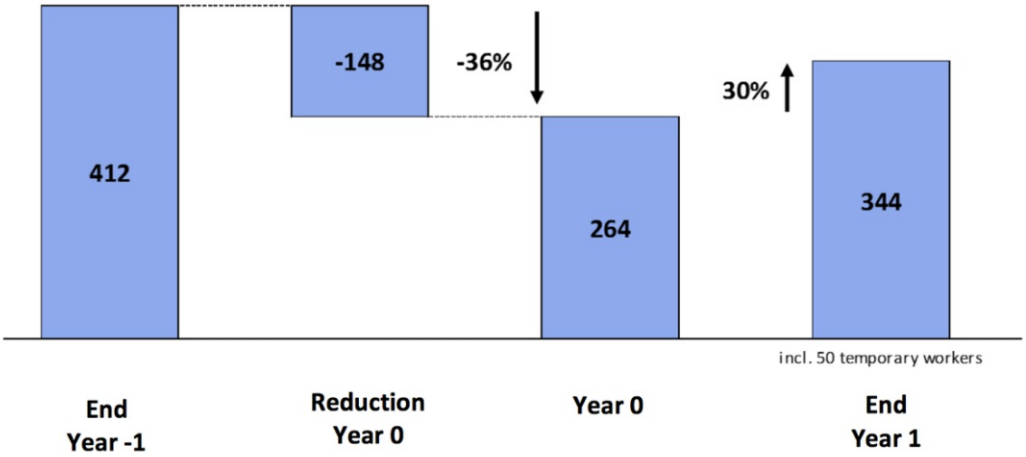

Figure 16: Headcount Development Before & After the Restructuring Programme Decision

As all existing shop floor workers were only trained to work in one position in one production line, a cross-functional training programme was initiated, where all shop floor operators were trained to be able to swap positions to different production lines as well as to different work stations (Figure 17). This added flexibility to the production lines and allowed for shifts from one production line to another depending on demand and capacity requirements. A similar approach was also taken in the Engineering Department for Design Engineers as well as in the Order Execution Department for all Project Management Positions. Furthermore, it reduced the impact when a staff member resigned as there were available contingencies. This allowed the company to effectively permit an adapted flow approach to level the capacity and the production orders and absorb some of the peaks and throughs of demand.

Step-by-step multi-functional teams with specific improvement objectives were established to allow better communication across the organisation. They were set up to operate as self-directed work teams with different areas of expertise. This allowed for a much quicker recovery and the improvement of the overall operation. The project management team was appointed as the leader of an incentive named 'mission control' to improve on-time delivery of products. Team members were made up of the Supply Chain Department, the Production Department, the Quality Department, and the Engineering Department, and the team leaders had the power to call in any additional function that was relevant for the success of projects, e.g. the customs

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clearance team if imports were held up or the finance team if a supplier was not paid on time. Furthermore, they had the responsibility to report on the progress of any one project and the right to escalate a problem if they did not see sufficient progress.

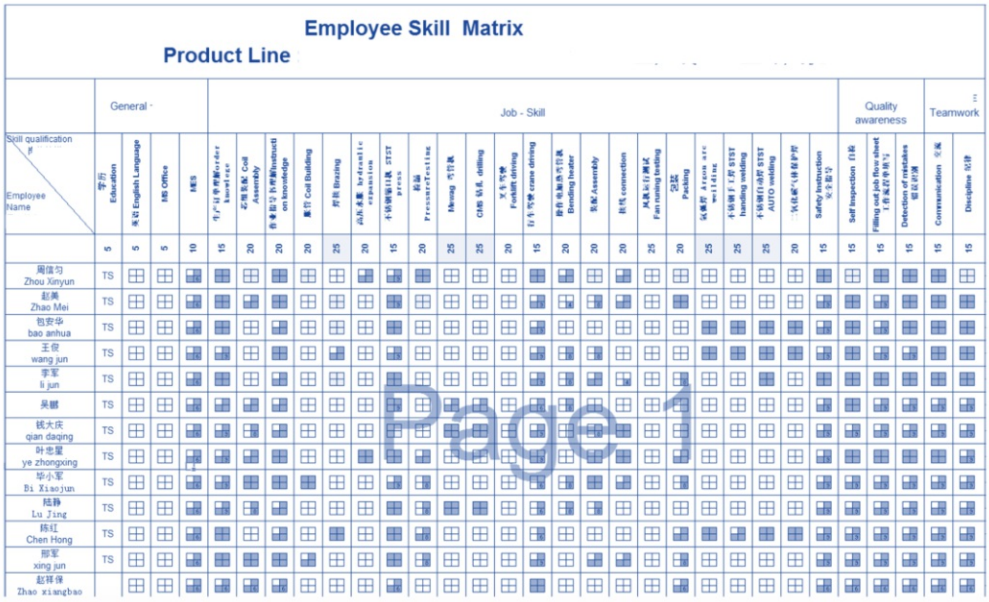

Figure 17: Skills Matrix for Cross-Functional Training for Various Work Stations

Another cross-functional team was dedicated to Lean implementation focused on operational excellence. This team was led by the Design Department, in particular the process engineering function, and made up mainly of team members from the Production Department, the Quality Department and the Logistics function. While the team predominantly looked at shop floor related waste removal, identification of improvement potential in other overlapping areas was welcome and encouraged. Bottleneck identification, production layout improvement, takt time improvement and process improvements were some the responsibilities.

Moreover, each function was incentivised to perform regular *gemba* walks both related to their own function as well as related to potential shop floor improvements, including 5s and other recognised waste identification. Also, *asaichi,* or morning meetings, were reintroduced to the production lines. This was particularly relevant during shift 'handover' for those lines that were operating more than one shift. It was also an important way to review the expected tasks for the day or the shift, and an opportunity to exchange information between work stations.

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To allow for better staff retention, all staff were encouraged to apply for internal job openings as well as evaluate job rotation possibilities. This improved the knowledge across functions and helped to reduce the walls that had been allowed to be built between departments.

New key performance indicators (KPIs) were introduced across all functions but in particular in the Production Department. In the past the Production Department was penalised when production orders did not leave the plant in-time, irrespective of whether or not they were able to influence the delay. So, the performance measurement was changed from on-time delivery to on-time production. The number of projects that could be produced within a given month was defined at the start of the month as the total production value target. For the Design & Engineering Department the measurement of on-time routing and bills of material was introduced. The new approach of measuring only the performance that each employee effectively had the power to influence, drastically improved the overall performance of the plant.

As may be expected in such a volatile and unstable environment, where changes are inevitable, and the general mood is bleak after two rounds of substantial layoffs, the staff were initially very demotivated with some outright hostile. Consequently, in particular the cross-functional teams and the job rotations were an opportunity to build trust and break down barriers. In the beginning, there also were regular fall backs to 'bad old ways' and some reminiscing about the 'better years' that had been experienced when there was little to no competition. Hence, at the beginning the required trust was hard to build up. And later it was challenging to keep up the necessary momentum to sustain the Lean improvements that had been achieved. It helped that new members of staff had joined and watered down some of the resistance.

4.3.3. Design and Engineering Department

After the customer order was received, the Design and Engineering Department was the first counterpart within the plant that had contact with the customer. The process of fulfilling the order generally started with communication with the Design and Engineering Department. Specifications of the customers were translated into a bill of materials (BOM), product drawings, and routing for a definition of the production process within the plant. Before the completion of this 'translation' step, no further

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preparatory steps could be taken. Thus, procrastination in the design and engineering step inevitably led to delays in material orders and production scheduling. At the beginning, the process was at times longer than scheduled, also leading to delays. One reason was that during the layoff critical team members had been dismissed. Consequently, these positions needed to be refilled. However, there also was a general lack of visibility of tasks and progress. The engineering team struggled with poor communication with the Sales entity, and the customers. Moreover, there was dependence on sister sites that were expected to support as 'centres of excellence' for specific product groups. However, often their own priorities did not allow for timely assistance.

Visualising the relatively long engineering lead times as well as the delays, concentrated minds to identify possibilities for improvement (Figure 18). Waste, in the form of waiting for sister sites' support or feedback from customers, was eliminated. Furthermore, it helped to identify bottlenecks such as a shortage of critical design engineers.

Additionally, the process helped to identify a waste related to a lack of an interface software to link the computer aided design (CAD) engineering software to the enterprise resource planning (ERP) system. This meant that the bill of materials generated by the computer aided design software needed to be physically re-input into the enterprise resource planning system. While this led to waste in the form of time and personnel, it also lent to making input mistakes with far reaching consequences.

As the Engineering & Design Department had the best technical understanding of the structure of the product, it was often helpful to involve team members in the discussion with suppliers in how to manufacture particularly complex parts or parts that required particularly tight specifications. Therefore, cross-functional teams were set up and led by the purchasing function to explain technical requirements to suppliers and discuss how best to manufacture the parts.

The Engineering and Design Department also got involved in discussions with the production team to evaluate the best, fastest and most efficient way to manufacture the final product. This was particularly relevant when new products were launched

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and when a particularly challenging new design was introduced to existing products. In these instances, it was similar to the production of a prototype.

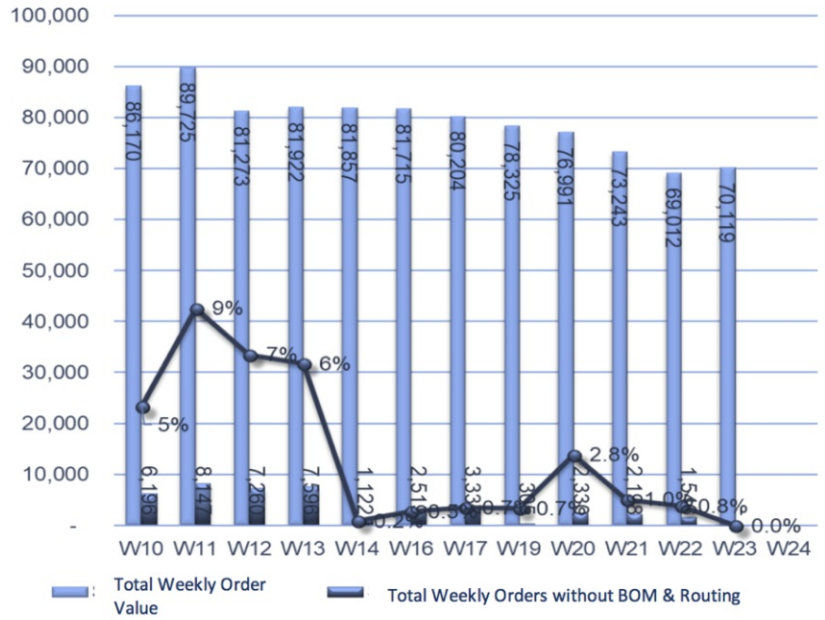

Figure 18: Engineering Delays Visualised

As the routing originated in the process engineering section of the Design & Engineering Department, it was the right starting point to initiate process improvements. The process engineering function looked at each production line and evaluated potential for waste reduction. This could mean reduced transportation of parts due to better positioning of work in process parts or elimination of process steps that did not add value or improved ergonomic positioning of fixtures or improved jigs or more suitable machines. Additionally, a programme for design for manufacturability (DFM) was initiated where the design of a product was re-evaluated with a focus on how it can most easily be produced with the least effort, the least materials and the least processing. This could also involve the implementation of *poke yoka* tools to avoid making mistakes especially during assembly. Attempts at modularisation were also made, where basic structures could be common and auxiliary parts were customised.

4.3.4. Supply Chain Department

The Supply Chain Department was in charge of the supplier development function, the order placement function, the warehouse management function and the logistics

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function including import, export and customs clearance. As the complete order fulfilment was in such disarray, there was a lot of pressure on the Supply Chain Department to ensure timely delivery of parts. However, the company had neglected to continue developing new suppliers and was faced with a single source for many critical parts. Furthermore, in an engineer-to-order setting, finding interested suppliers can be challenging as the product portfolio to be purchased is also high-mix-low-volume with a high level of complexity, and many suppliers are simply not interested.

4.3.4.1. Supplier Management

As many parts were delivered late causing delivery delays for Company A, one urgent area of focus was improving communication with existing suppliers to identify what could be done to improve the supplier on-time delivery. The second area of focus was to locate potential new suppliers, and together with the Quality Department audit them with a view to being able to qualify them. As the suppliers had very little visibility of potential orders from Company A, often the capacity at the suppliers had already been booked by other customers. Poor communication also regularly led to poor understanding of parts' technical requirements. Consequently, parts were regularly defective or did not fit. Some needed to be scrapped causing further delays, while others could be reworked. Improved communication with suppliers as well as the development and certification of new suppliers helped to improve the supplier on-time delivery and consequently helped to reduce waste (Figure 19 & Figure 20).

Figure 19: Development of Supplier-on-Time Delivery for One Particular Part

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Figure 20: New Supplier Development

The improved supplier relationship also assisted the overall order placement, as the suppliers were able to book capacity in advance and technical queries were answered in a timely manner. It also helped to decrease the need for incoming goods inspection, and consequently reduced the workload for inspectors. The long-term commitments on contracts helped to build trust and enhanced the willingness to make investments for future projects.

Moreover, for certain items vendor managed inventory was introduced. This helped reduce the material planning effort. Parts were evaluated according to an ABC analysis and especially for regularly reordered C parts of low value, such as screws, rivets, bolts and washers, vendor managed inventory was very useful. Also, consignment stock was introduced for recurring parts of high value but with less variety.

Monthly supplier evaluations were introduced to track the development of suppliers and provide visibility of improvements. The monthly supplier evaluation contained information on lead time, quality, supplier-on-time delivery, and was regularly communicated to the suppliers. Furthermore, contracts were reviewed and standardised to have clearer mutual expectations.

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4.3.4.2. Warehouse

As it had become painfully evident that the outsourcing strategy for the warehouse management did not provide the hoped-for results, the warehouse was insourced again. Figure 21 illustrates that out of a total of almost 4000 items only 2100 were correctly managed when the warehouse handover took place. As all warehouse staff had initially been laid off, a completely new team had to be recruited, trained and familiarised with the parts portfolio. Steadily, the number of misplaced and lost parts successively decreased. The location of parts in the enterprise resource system and the bin locations had been regularly incorrect. This also improved consistently with the new team being in place. Regular cycle counting was introduced, which tangibly improved the inventory accuracy.

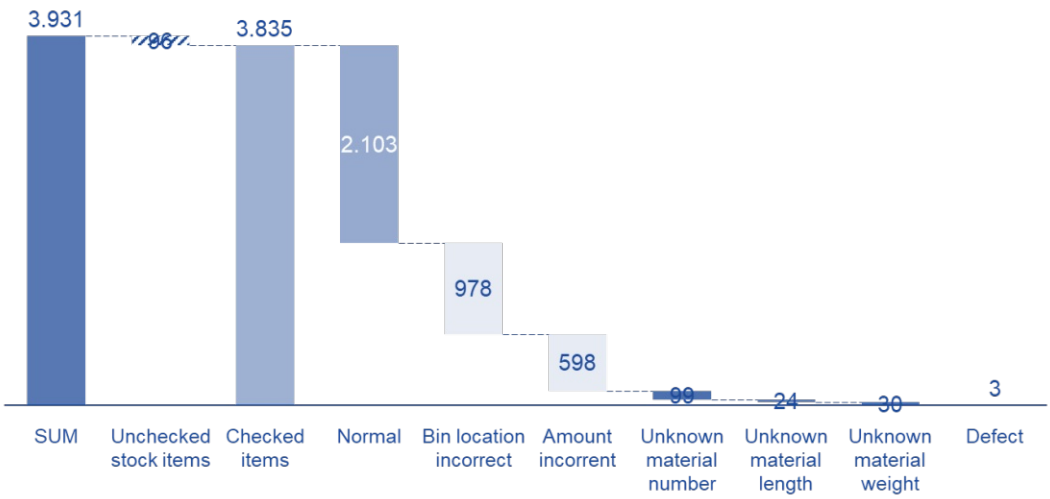

Figure 21: Parts Identification in the Warehouse at Handover

Kitting was introduced for all production lines, and operators were no longer burdened with searching for the correct parts. All parts were delivered to the production line instead. This reduced waste in the form of searching, waiting, handling and transportation.

4.3.4.3. Logistics

Due to the reliance on a single source strategy, the reliability of the transportation suppliers was not sufficient. This also led to poor prices. Despite increased orders in Year 1 as compared to Year 0, the overall logistics spending was drastically reduced (Figure 22). The improved communication with the logistics suppliers

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ensured that orders were picked up and delivered on time, while imported parts were cleared from customs more in a timelier manner, and consequently, received faster in the plant. Of course, the increased supplier base also improved the overall availability of capacity. Furthermore, the monthly performance evaluation was also extended to all logistics suppliers.

Company A experienced a similar situation with the packaging material supplier, where a single source strategy had also been in place. As most of the final products manufactured by Company A are not of a standard size, and some final products are particularly large, packaging companies are required to custom-build packaging. In order to reduce the complexity, Company A engaged a design company to draft standardised packaging in a modular approach with scaled sizes. This increased flexibility and reduced the cost. Furthermore, it allowed the company to move away from a single source strategy.

Figure 22: Monthly Comparative Logistics Spending Development

4.3.5. Project Management and Order Execution Department

The Project Management and Order Execution Department functioned as the link between the customer and the operation, and coordinated the communication on any given project. It was also responsible for identifying potential difficulties of ongoing and future projects and ensure their resolution. However, with the number of delays

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and overall difficulties encountered by each project, the project managers spent considerable time on placating the customer rather than solving the project issues.

Early in the Lean restructuring programme, a cross-functional team called 'Mission Control' - to suggest the pivotal importance of the team - was set up. All critical functions were organised around product groups to form part of the team. The team identified concerns and bottlenecks relating to the implementation of the project and met every morning in the sense of *asaichi*. The project managers led the teams and were empowered to push critical issues. Where progress was not adequate and projects were threatened by delay, they had the responsibility to communicate this to the next level of management and if necessary to top management. Regular bi-weekly follow-up meetings with the management team were also scheduled where progress was reported. Project managers and other team members also went on regular *gemba* walks on the shop floor to follow up on the physical progress of the projects and to communicate with operators on any possible concerns.

One major difficulty in ensuring a smoother and more levelled production and general order execution process was the very high level of customer order change requests. This was related to the fact that contractually there were no disincentives for customers to do this. On a monthly basis on average 400 orders were placed. Figure 23 highlights the severity of this problem, which led to terminal rescheduling of production orders and material purchase orders, and also made suppliers unhappy. Furthermore, it negatively affected lead times as the permanent rescheduling required a lot of effort, time and resources that could otherwise be employed more constructively elsewhere – another type of waste.

Figure 23: Weekly Requests by Customers to Change Delivery Times

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Consequently, a concept of a 'frozen zone' was introduced (Figure 24). Customers could change their orders up to the point when orders for parts were submitted to suppliers. From that point onward, Company A charged for order rescheduling to provide a disincentive to customers to change their orders. This approach was successfully operating in several of the sister plants and was used for benchmarking and the introduction to Company A.

This approach helped to stabilise the orders, the production scheduling at the suppliers, and the production scheduling at Company A. Furthermore, it made it possible for Company A to commit to purchase a certain amount of confirmed capacity at critical suppliers, and it consequently made an overall reduction in lead time to customers possible.

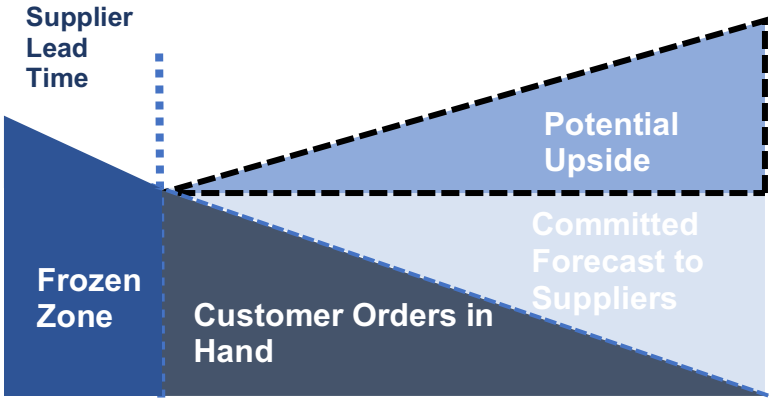

Figure 24: 'Frozen Zone' Concept to Stabilise Order Processing and Improve Lead Times

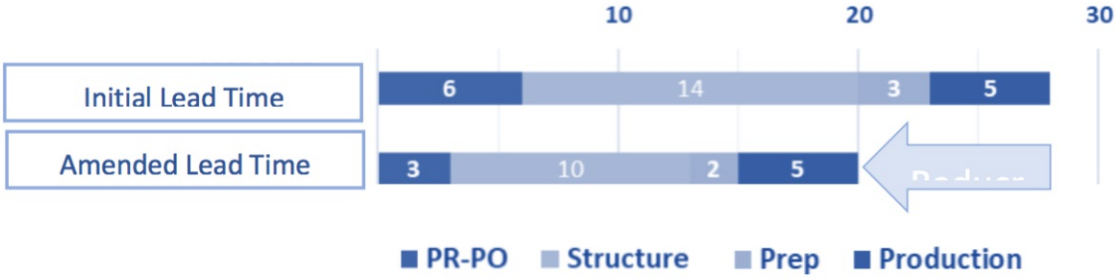

Figure 25: Lead Time Reduction for One Product Line

Of course, this new approach also required closer communication with the customer. At the outset it was challenging to convince the customers – and maybe even more

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the Sales entity – that this approach was necessary and actually also provided benefits to the customer in the form of improved lead times and a firmer commitment on the product on-time delivery. The new approach permitted the Project Management and Order Execution Department to move the conversation away from delivery delays to an improved customer offer.

For the parts order placement process, Company A also used an adapted form of value stream mapping to identify waste. Initially, the parts order placement process was very complicated involving many steps, some were releases at various levels where necessary. The re-evaluated process helped to reduce the overall lead time and freed time for staff.

4.3.6. Production Department

The Production Department was in the unfortunate position to be at the end of the order process, meaning that in the beginning they were required to show a disproportionate level of flexibility to buffer disorganisation across the process. At the same time, there was a lack of adequate organisation on the shop floor compounding the problem. A basic level of 5s is necessary before it is even possible to consider implementing any Lean practices. Consequently, Lean teams were formed in all production lines with one operator chosen to lead the team. With the support of the Human Resources Management Department basic 5s training was introduced and regularly reinforced. This removed the clutter from the shop floor and assisted a general sense of 'housekeeping' where every operator was in charge of their particular work station including cleanliness, tools management and basic care for the machines in their charge. A new key performance indicator was added to the monthly incentives to follow up on the 5s implementation to ensure sustainability.

Clearly, waste right across the process was pervasive. A steady flow of production was impossible due the recurrent waiting periods for either material to arrive, parts to be reworked, parts to be searched for, machine breakdowns, tools getting lost, accidents occurring due a lack of appropriate equipment, lack of training or sheer carelessness. Clearing up the shop floor was therefore a necessary first step to regain control over the process.

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Almost all products required stamped parts from the punching machines. So, after the new maintenance team had come together, a natural second step was to perform basic maintenance on all nine presses, as a breakdown risked a line shut down. A team from a sister site was scheduled for regular visits to support the operation in setting up an improvement programme for the presses and the matching moulds.

Concurrently, processes were improved in order to identify opportunities for improved productivity. Step-by-step, each production line was evaluated and potential for improvements identified and prioritised. Process layout, bottleneck identification, staffing, one-piece-flow potential, process improvements, machine reliability, cycle time, transportation, safety, work in process were all aspects under evaluation. As the products and the difficulties in each line were so different, it needed to be done production line by production line.

In general, the nature of engineer-to-order defined that the production was entirely based on a pull system. As all products were customised or engineered, products were not made-to-stock. The difficulty was to predict demand and to find a way to level the capacity. This was also one reason to cross-train operators. This meant that when demand was low in one production line and high in another production line, operators could jump between lines. At the start there was resistance to job rotation, as in the past operators were dedicated to a fixed production line and work station. Eventually, the increased exposure and the opportunity to learn was seen as a benefit and therefore welcomed.

While a basic level of standardisation had been implemented, e.g. all work stations and processes had work instructions, what was available was often no longer applicable as processes or tools had been changed but the corresponding documents had not been updated. Also, the sheer number of very different products and processes made a meaningful level of standardisation difficult (Figure 26). With 400 average monthly orders and a total monthly volume of 1500 products, average lot sizes were less than 4 products in 11 production lines.

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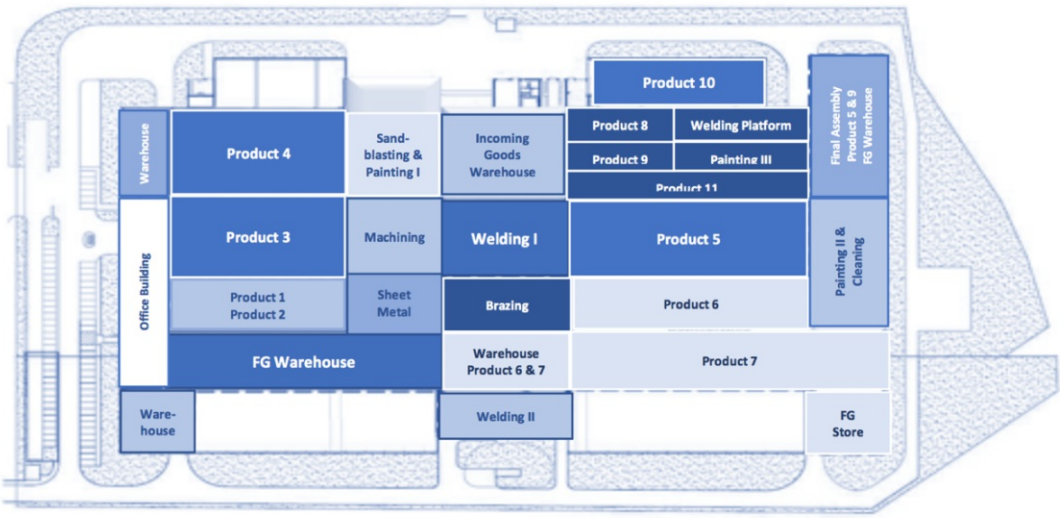

Figure 26: Plant Layout

4.3.6.1. Product Group 1

Product Group 1 faced the difficulty that the product was completely manually assembled, and that the parts were heavy and cranes were required for each step. That limited the layout to the dictate of the crane layout. After the completion of the basic 5s housekeeping, shelving for parts and tools was set up near the work station to reduce motion.

One challenge was to lower the total time required for assembly and testing. So, the individual assembly steps were analysed by the Operation Excellence Team together with the production line team to identify potential savings and possibilities for ergonomic improvements.

A decision was the taken to arrange the product assembly in a cell layout as the products were compact and did not require any major manufacturing content. Trolleys with parts and tools were arranged around the work stations to reduce movement and transportation. The work stations had to be near a water source for testing the final product. Bolt tightening equipment was changed from a heavy and rather cumbersome hydraulic one to an easier and lighter one using compressed air. The parts were kitted and then delivered to the work stations where they could be assembled and then undergo final testing (Figure 27). As the orders were discrete and quantities did not exceed five pieces, there was no work in process in the line.

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4.3.6.2. Product Group 2

In the entire plant, production line for product 2 was the closest to a serial production. The process required a punching press and a brazing furnace. The products were relatively small and light-weight and consequently did not require a crane. The production line was arranged in a line and organised according to functions (Figure 27). The production orders were processed in batches. Customisation happened before the brazing process where customer specific connectors were required. This production line did have work in process.

In this line the bottleneck was the furnace, which could only process a predefined quantity of parts in one production run. The only way to eliminate this was to invest in a new furnace, which at the time was not feasible. Consequently, quantities were limited to the quantities that could be produced within three shifts.

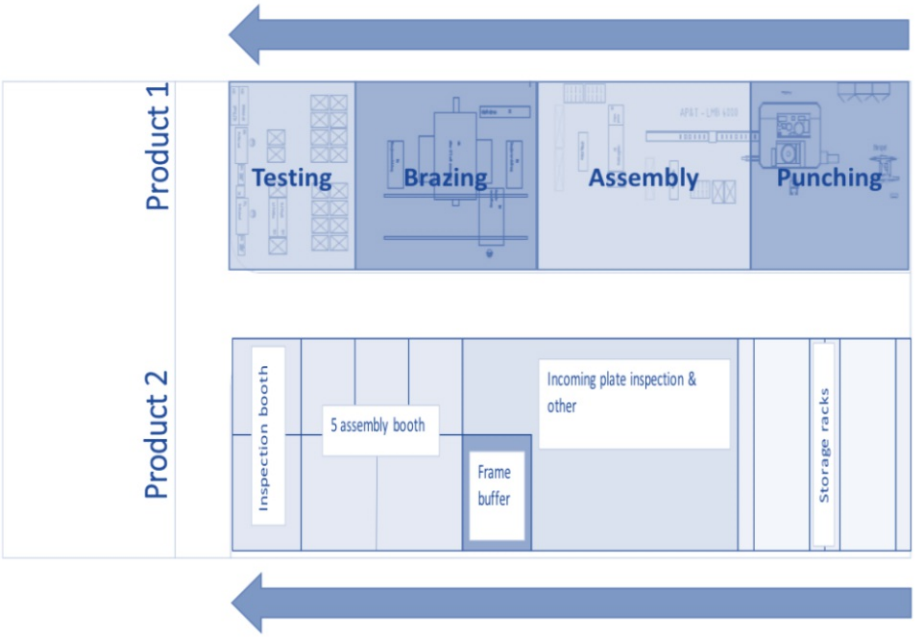

Figure 27: Layout of Production Area 1 & 2

4.3.6.3. Product Group 3

Product 3 required substantial processing. At the start of the process stamped parts were manufactured. For these parts tool changes were required and the capacity of the punching presses was tight. This led to large quantities of work in process that

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was placed near the lines cluttering the area. The products required to then be assembled manually, but necessitated the operation of cranes as the products are heavy. In a next step, tubes were expanded with specialised equipment in a semi-manual process. This was followed by another manual assembly step and a final testing step. The production line was organised in a U-shape, in a line format, due to the crane operation. The production was organised in batches in accordance with the customer orders, as all products were engineered

As the overall volume of this line was relatively large and an increased level of demand was visible, it was important to identify possibilities of increasing the total capacity. Again, the first step was to implement 5s housekeeping. Each work station was organised with a view to defining required tools and auxiliary material, and providing ergonomic positioning of shelving and tool trolleys to reduce movement and allow easy location of necessary items. The material and the tools within the line were analysed, reviewed and defined. Large amounts of work in process was removed and placed in dedicated warehouses to improve visibility in the line. This work in process material was later released back into the line, when it was required for production orders. As the press capacity was limited, a certain amount of semi-finished goods was unavoidable, and designated storage space was defined and managed by the warehouse team. However, the production of semi-finished stamped parts was optimised to reflect ongoing orders.

One critical step to improve the overall capacity was to improve the capacity of the punching presses. With the improved maintenance of the presses, the downtime improved. However, the handling on the presses was suboptimal. The operators regularly stopped the press when enough parts had been stamped to move the semi-finished parts to a designated collection area from where it would be moved either into the storage area or into the production line. While the machine was stamping the parts, the operator simply waited. Therefore, additional jigs were purchased to stack material released from the press. So, the operator could then move the material to the collection area, while the press was stamping additional parts. Machine data was then regularly collected and made visible to quantify the progress and follow up on further improvements.

After the capacity problems with the presses was resolved, the bottleneck moved to a process further along the production line. This process again involved critical

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equipment, where capacity was limited. Here a machine was ramped up by adding an additional machine part that effectively doubled the capacity of this operation.

Many smaller improvement steps were taken to reduce inefficiencies and reduce waste. Minor investments in specific customised tools and jigs assisted in-process improvements. For example, the investment in a small turning machine released the capacity of one of the Computer Numerical Control (CNC) machines in the machining section. Of particular importance for this line was the commencement of kitting. This speeded up the processes disproportionately.

Streamlining the painting process assisted one further fundamental elimination of waste. In the past the parts on this line were initially painted in a first step. They were later assembled into the end product and then painted again. This made it easier for operators, as they did not need to take too much care about damaging the parts when handling the product. However, this was clearly an unnecessary form of waste in the shape of handling, process, transportation and additional material requirements. Consequently, the painting process for this product was reduced to only the painting of parts.

4.3.6.4. Product Group 4

This product is similar in structure and process to Product 3. However, it is much larger and heavier and the overall production volume is only around 10% of that of Product 3. Also, the specifications of parts regularly are tighter than those for Product 3.

The layout of the line was similar to that of Product 3, but requiring more space and larger cranes. The line was also organised in a U-shape along straight lines starting with the punching process. Products were manufactured discretely or in small batches. As the products were large and heavy and required to be completely turned around, safety was a major concern. Therefore, a custom-built jig was designed and ordered to assist in the safe turning of the product, therefore also decreasing the handling time.

In this line work in process of stamped parts was also a problem. Like for Product 3, work in process was therefore collected and placed in a dedicated location from which

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it would be returned when the production order was released. All material was kitted and placed in the line only when required.

For Production Lines 3 and 4 there were many auxiliary parts like nuts, screws, bolts and washers that were placed at the far end of the production line. This meant that operators regularly had to go to collect these parts, wasting time and requiring a lot of movement. The parts were moved to shelving closer to the work stations to reduce movement and kitted by the warehouse team.

4.3.6.5. Product Group 5

This product was exceptionally large, heavy and wholly engineered. It required assembly, processing, tube expansion, brazing and testing. As the product's size was so large, the related machines were equally large. The tube expansion process required a machine with a length of 15 metres, while still allowing enough width for the product to be placed next to it. The tube expansion machines in other lines were able to expand several tubes at the same time. However, for this product this was not possible. The Operations Excellence Team together with the Maintenance Team and the production line team evaluated possibilities for improving cycle time for this process. An investment in a technical addition was subsequently made that allowed the cycle time to be reduced by a third. As Product 5 had many more tubes to be expanded due to its size, this made a tangible difference.

The product then had to be tested in a large tank and was thereafter moved to the assembly area. Again, the size and weight of the product put constraints on the potential for further improvements in the process. However, kitting did make a big difference in reducing waste, in particular in the time required by operators to locate the right parts. Also, 5s improvements ensured that all required equipment was placed in shelving near the line.

4.3.6.6. Product Group 6

This product is sizable as well as heavy with a significant volume. Orders were generally placed in batches of five to twenty products with identical design making production in batches compelling. As the processes were consecutive, a line layout was fitting, allowing for easy crane use and a relative flow production.

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Improvements were made by introducing automatic tube welding. This allowed for several tubes to be welded at the same time halving cycle time. But it also improved the quality of the welding seam, enhancing the safety of the final product.

Likewise, this line had undergone basic 5s housekeeping, where unnecessary parts and tools were removed from the line, shelving and tool trolleys placed in strategic, easy to reach positions and excess equipment removed from the line.

Additional fixtures were purchased to make the process more ergonomic. Assembly work tables were changed to be adjustable to make assembly easier and safer for operators.

4.3.6.7. Product Group 7

This was the only product that was produced very close to a one-piece-flow as the volume was reasonably large and the variants, while not small, were limited in number. Also, the existing variants were similar in overall design, making a modular approach possible. The process started from the punching presses moving on to bundle building in a manual assembly, progressing to the brazing stations, then mounting of fans ending in the final assembly, testing and packaging before being moved into the finished goods area (Figure 28).

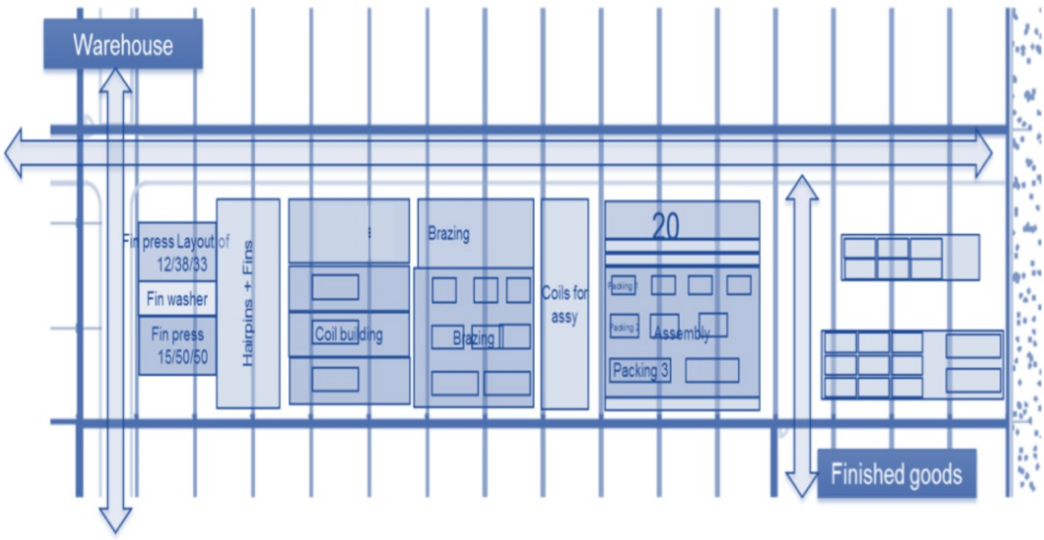

Figure 28: Layout of Production Area 7

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Again, the Lean approach first necessitated a general housekeeping with 5s tools. Over time the one-piece-flow concept had been corrupted and stations were moved disrupting the flow. This was put back into its original concept and improved upon. This also eliminated the double handling of parts and product. Additional movable work stations with height adjustments were added to make work stations more ergonomic allowing for easier flow. To improve visibility, the initially considerable amount of parts near the line were removed.

4.3.6.8. Product Group 8

These products were relatively large and heavy and required numerous production steps including welding, assembly, sand blasting, painting and testing. As the distances covered to manufacture Product 8 crossed numerous individual shop floor areas, this meant that it was not possible to make use of the cranes to transport the products. Consequently, all products had to be transported with a forklift, adding to unnecessary waste. As can be seen in Figure 29, the products were transported back and forth numerous times before they were completed. As the products allowed for manufacturing in a one-piece-flow process, the Operational Excellence team identified this as an obvious improvement measure. The complete process was simplified allowing the consistent use of cranes and a step-by-step production (Figure 30). This reduced the transportation and handling time immeasurably, and also improved safety.

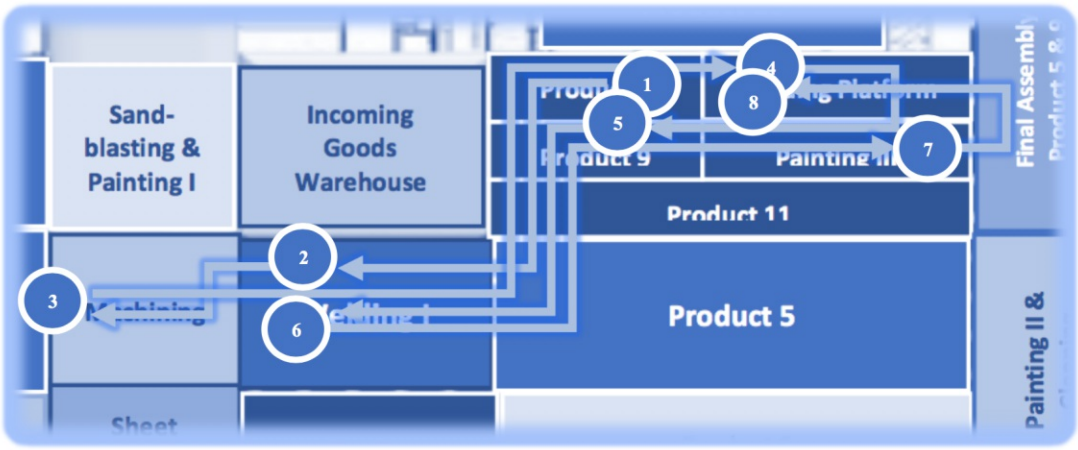

Figure 29: Initial Production Process Layout for Product 8

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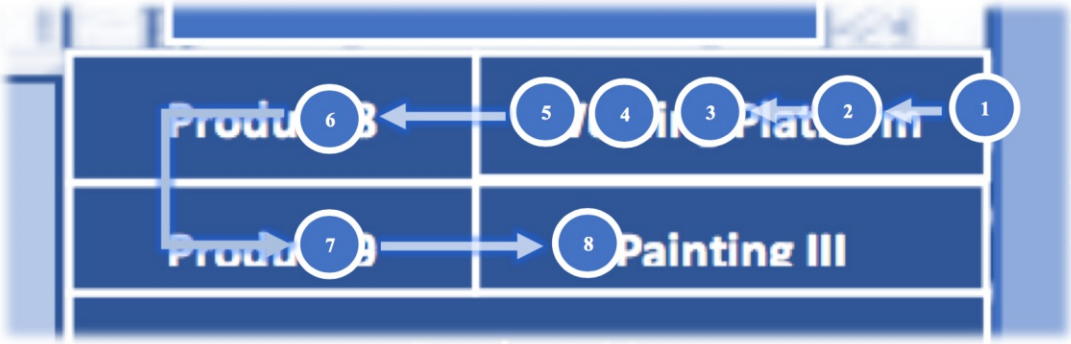

Figure 30: Amended Production Process Layout for Product 8

However, this line was facing an additional safety issue as the existing welding platform did not meet safety requirements. It was therefore imperative to invest in a new improved welding platform, which could be positioned in a more suitable location to improve efficiency. Furthermore, it made it possible to redesign the welding platform to allow more than one product to be manufactured at any one time, effectively increasing the capacity. As the welding platform was also used for Product 11, this allowed for efficient use of the investment (Figure 31).

Smaller efficiency improvements were also introduced, where parts were not sand blasted piece-by-piece but in batches, increasing the overall volume. Shelving and racks were placed in strategic positions to reduce movement.

4.3.6.9. Product Group 9

This product group has a relatively high manual labour content, and the product structure varies considerably from one order to the next. This makes it impossible to standardise the process flows. As there is a considerable manual assembly content, the organisation in cell layout was most appropriate. This allowed the base of the product to stay in the same position, while the operators moved around the product to complete it. Numerous parts needed to be assembled on the large base. Kitting was critical to ensure the reduction of unnecessary movement.

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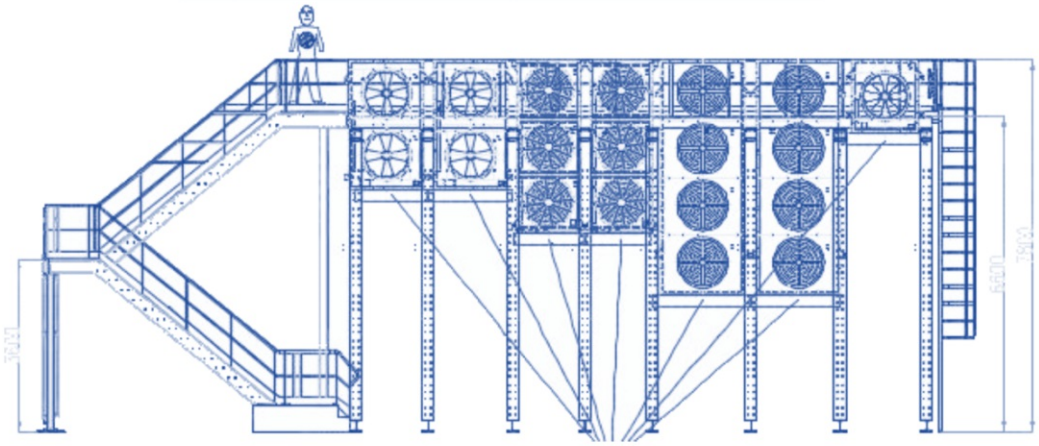

Figure 31: New Welding Platform

4.3.6.10. Product Group 10

This product was entirely organised in a cell layout, as the product is relatively small with few variants. Here, a production levelling was possible as the demand was relatively steady and the variability was limited. In this line the bottleneck was identified as the testing station. Revamping the testing station improved the overall capacity.

4.3.6.11. Product Group 11

The structure of Product 11 resembles that of Product 8, and is therefore manufactured in similar steps. However, when the product is entirely stainless steel, it needs to be produced in a separate production area designated for only stainless-steel production where no other metals are processed. Also, the testing processes are different. However, the new layout in Product Line 8 mostly also benefitted Product 11 directly.

4.3.6.12. Machining & Other Supporting Manufacturing Functions

At the outset, the welding department was in dire need of 5s implementation. Many parts were stacking up in corners, and obsolete equipment was cluttering the work stations. Part of the difficulty for the welding department was that they produced parts for product groups, which meant that the variability of parts, quantities, shapes, sizes

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and weights was endless. Additionally, Product 8 and 11 were also welded in the welding department making any sort of scheduling near impossible. Consequently, the Operational Excellence Team identified the need to separate the two types of welding processes as they also followed different welding standards. This improved the productivity and reduced waste related to transportation and movement. It also assisted the production scheduling.

The machining department also benefitted from the new process for Product 8 and 11 as the products were no longer machined in the machining workshop. The machining process was also moved into the newly designed production line. This removed the interruptions that resulted from the need to finish the production of Product 8 and 11 in the machining workshop.

However, for the machining department the overall biggest benefit resulted from improved, regular maintenance. This reduced the machine downtime, and efficiency improvements reduced cycle time. Increased inhouse spare parts maintenance for the computer numerical controlled (CNC) machine, also improved the quality of parts and reduced scrap and rework.

The painting department was also affected by the two layoffs necessitating the employment of a new painting specialist to lead the painting team. All products except 1 and 2 required painting. The difficulty was compounded by the fact that a part of the painting process was outsourced to a third party operating on the premises. Improved housekeeping in the form of 5s was also a necessary first step in the painting process. Improved drying racks eliminated time consuming rework and patching up. In a second step, the outsourced painting work was insourced again, reducing the overall spend and improving the on-time delivery of parts as well as finished goods.

The sheet metal section was highly automated and was operating smoothly based on a functional set up of the machines. However, the overall material consumption was relatively high. Efforts were made to reduce this using software to fit the individual parts better onto the metal sheet. This allowed for an improved scrap rate.

The brazing department required an entirely new layout. The process favoured a functional manufacturing set up, where individual work stations were specialised in

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brazing particular parts which then fed into the production lines. Each individual work station was reassessed to minimise movement, installing shelving designed to hold parts and conveniently make tools available. Finished parts were moved to a designated area, which the warehouse team then picked up and moved into the respective production lines.

4.3.6.13. Total productive maintenance

One of the most urgent steps for the production was to ensure that the nine presses, some of which had been in operation for several years, would not break down. Colleagues from a sister site, together with a team from the production line, and members of the maintenance team formed a multi-functional team to identify potential for improvements. In a first step, all presses had undergone basic maintenance and an evaluation of their current state. A list of weaknesses was then collected to step-by-step eliminate any problems. Some problems could be solved in-house, while others required the support of outsourced third parties. At the same time the dies were overhauled. A new die specialist was employed, who then got specific training at the sister site. Progressively, the problems were resolved and a structured approach to maintenance was taken, where emergency maintenance was replaced by preventive maintenance. For each machine a list of wear-and-tear parts was compiled. Average replacement times were defined based on number of punches, where the machines were then overhauled in regular intervals and parts were replaced. All critical parts were defined and put in stock. Moreover, a small workshop for the punching die engineer was set up, where the dies were regularly maintained.

At the same time, the possibility of quick changeovers for the dies was evaluated. Additional jigs made it possible to more easily remove and replace the dies in the machines. Furthermore, the process was optimised and the total time requirement was reduced by of 30%-50% depending on the press. This allowed for more regular changes of dies, reducing the need to place a lot of work in process in the store or in the production line. Therefore, an element of production smoothing was possible. Also, the cycle time of the machine was analysed, and improvements to the machine operation as well as the handling process increased the overall manufacturing speed and consequently the capacity.
It can therefore be said that the overall equipment effectiveness (OEE) was improved. The machine time availability was improved as there was less downtime; the machine

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performance was improved as the process was sped up; and the quality was also improved as the cleaned and maintained dies produced less unqualified parts (first pass yield).

The machine park in the machining section was also in dire need of maintenance, where a similar programme of machine overhaul was followed by preventive maintenance. As the maintenance team was very stretched, due the vast number of machines and equipment that had been sorely neglected, there was pressure to train operators to 'own' their machines and take over daily housekeeping of the machine, such as greasing, refilling of oil or water, tightening loose bolts, and general daily cleaning and care of the machine. In consequence, the maintenance team was only called for assistance for major issues, that could not be resolved by operators. Therefore, some of the time of the maintenance team was freed for more essential tasks.

The second painting line and the sandblasting unit were refurbished, when the painting line was insourced. The extraction system was upgraded and the painting nozzles were renewed. This improved the speed and quality of painting and reduced the time required for each production lot.

Successively, all machines were maintained and re-evaluated and a preventive maintenance programme was implemented. The overall leaner approach also reduced the overall maintenance spending year-on year by 40%.

4.3.7. Quality

At the outset the quality was expectedly poor and a substantial amount of rework was necessary to both parts as well as final product. Also, there was no *Kaizen* or continuous improvement culture in the company. As a result, finished goods that did not meet quality standards did leave the plant, damaging the company's reputation and leaving customers severely dissatisfied.

While all formal quality requirements such as ISO9000 and ISO14001 as well certification for American Society of Mechanical Engineers (ASME) for pressure vessels and welding as well as for the Pressure Equipment of the European Union was up to date, the systems were not lived on the shop floor. The overall 5s approach

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to improve housekeeping was a necessary first step for the quality team to be able to follow up on quality improvements. At the outset, quality inspectors were regularly put under pressure not to issue non-conformity reports (NCR), as the underlying philosophy of eliminating the root cause was not understood.

Regular training across the organisation was scheduled to improve the comprehension and more importantly to implement a quality management system. This assisted to lay the ground for a quality culture that allowed a continuous improvement approach. The training – in a scaled down version with a slightly amended focus – was also made available to critical suppliers.

Recurring detailed monthly quality reviews were introduced, where all production teams, the quality team and key staff members from other departments were present to review the quality issues of the past month and discuss steps that needed to be taken to avoid these issues in the future. Also, monthly supplier performance reports were collated, reviewed and discussed with critical suppliers. This made it possible to observe incremental improvements of critical performance measures and allowed for successive adjustments. It also helped to instil a 'quality culture', where all stakeholders understood that 'quality at source' was highly valued to reduce waste.

Each production line set up a dedicated cross-functional continuous improvement team, that reviewed quality issues, overall improvements and their implementation. Production steps, that helped improve quality, were implemented and standards and customer expectations communicated. The company reduced the internal and external cost of poor quality (COPQ) by 30% annually.

The quality department was also responsible for the Health, Safety and Environment (SHE) function. At the start, this function was not taken seriously enough. In the heavy industry the risk of getting injured is exponentially higher than in most other industries. The parts are heavy and large, and either require a crane, a forklift or a palletiser to be moved. If the parts are not secured correctly, serious injuries are a tangible risk. Instilling a sense of awareness for health and safety is therefore a high priority. So, a monthly report reviewing the overall company performance and a critical review of risks was started with the all production lines and a representative of all other departments. This allowed to generate a sense of urgency for safety, health and environment.

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On the shop floor many small changes were implemented to improve safety, such as changing all lifting lugs from open hooks to self-locking hooks (Figure 32). These were replaced right across the plant amounting to several hundred hooks, which considerably improved safety. But equally, major safety improvements such as the welding platform were implemented. The new platform improved the safety of the staff during the welding process, while also ensuring that fumes from the welding process raised up and could immediately be extracted.

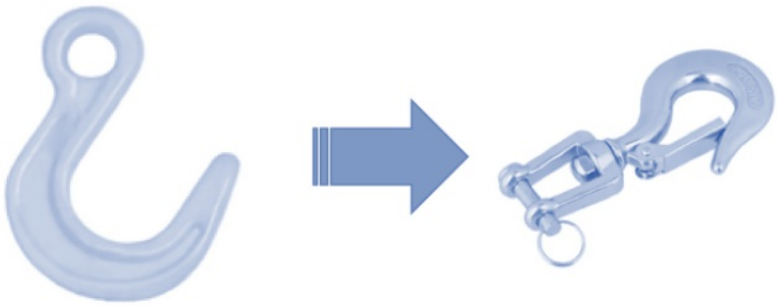

Figure 32: Lifting Hooks Replacement

Maybe the single most important step was to nominate one operator for each production line to be 'Safety, Health & Environment' representative. This role brought about prestige and an additional bonus. The representatives were trained regularly and reported cross-functionally to the Safety, Health and Environment specialist. Their task was to identify risks and suggest improvements in their line. Overall safety improvements helped lift the company from position 31 in the total Group of Companies to position 13 as assessed by an external risk assessment surveyor.

4.3.8. Performance Results

The Lean restructuring programme took time to gain hold in the company culture. While the introduction of improvement steps was characterised by speed and a sense of urgency, the more fundamental change of convincing the employees that a leaner approach was necessary and would be sustained, required considerably effort and consistency. However, the tangible results in performance improvement such as an increase of actual customer on-time delivery from 30% to 95% and a progression from being unprofitable to a 10% profit rate helped convince the staff on all levels that the Lean restructuring programme was both unavoidable and beneficial. As the

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successes were shared across the team through performance-based incentive, everyone had a motivation to participate and sustain the progress.

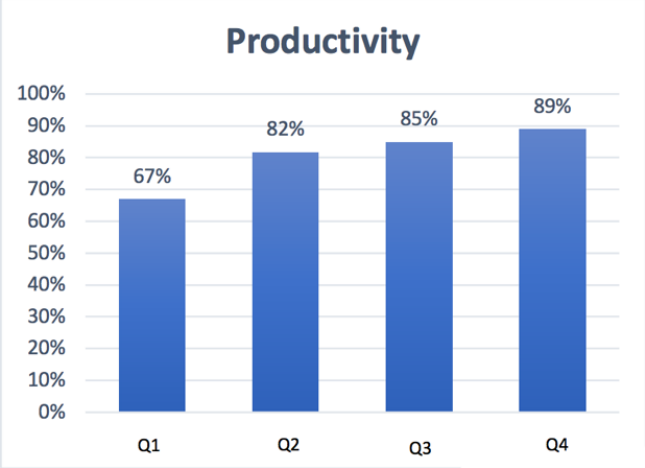

Figure 33: Productivity Improvement in Year 1

Although the overall challenge increased as the team had to sustain a 25% increase in turnover with the same headcount from Year 1 to Year 2, the overall improvement measures had sufficiently taken hold by then and made its achievement possible. The Production Department managed to progressively increase the productivity resulting in a 28% increase from Year 0 to Year 1 of the Lean restructuring programme (Figure 33). Furthermore, the lead times to customer were reduced for all product lines.

Company A missed all the Group targets for key performance indicators at the beginning of the Lean restructuring programme and always scored at the lower end of the last quartile of all sites. After the Lean restructuring implementation, it managed to meet and, in some cases, even exceed the Group's key performance indicators. The Group targets for Year 2 were 1.2% for cost of poor quality, 95% for customer on-time delivery and 15 days for lost time frequency injury rate. In Year 0, Company A started with a cost of poor quality of 6.2%, an actual on-time delivery of less than 30% and a lost time frequency injury rate of 13.1 days and in Year 2 progressed to cost of poor quality of 1.1%, an on-time delivery of 95% and a lost time frequency injury rate of 3.2 days. It also advanced from position 31 in the Group's safety ranking to position 13.

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Key Performance Indicators	Year 0	Year 2
Customer On-Time Delivery	30%	95%
Supplier On-Time Delivery	37%	93%
Cost of Poor Quality	6.2%	1.1%
Lost Time Frequency Injury Rate	13.1 days	3.2 days
Safety Ranking Position	31	13
Profitability	-5.2%	10.6%

Figure 34: Key Performance Indicators

Of course, this progress manifests a fundamental reduction in waste across all functions. In financial terms Company A managed to save considerable amounts in the more easily quantifiable areas of logistics, insourcing the painting function and reducing overall cost of poor quality leading to an overall saving of 2% of turnover. However, the improvements extended beyond this, allowing a profit margin of 10%. This means that all the incremental steps that were taken in reducing waste across all functions did bear fruit, even if it is impossible to attach a number to each individual improvement.

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5. Results: Lean Practices Customisation and Applicability

The case study has shown that for Company A it was possible to implement and make use of many of the Lean practices suggested in the bundles approach proposed by Birkie and Trucco (2016) and Shah and Ward (2003). This study therefore follows the findings of Birkie and Trucco (2016) and Birkie et al. (2017) that Lean practices can be implemented in an engineer-to-order environment and can assist to improve overall performance.

However, the ease of application of Lean practices varied across tools. Some Lean practices could be implemented directly without any modification, such as setting up multi-functional teams. Other practices had to be customised to have a meaningful impact, such as safety improvement programmes. At the heart of the problem is that classical Lean practices seek to remove what is valued in an engineer-to-order setting: variability and flexibility. Classical Lean practices seek to standardise and remove unevenness.

So, for a Lean restructuring programme to work in an engineer-to-order environment, it is necessary to evaluate how much standardisation and evenness of process is useful and can improve the overall functioning of the company. At the same time, it is necessary to look at how much variability and flexibility needs to be sustained in order not to reduce the value offer to the customer.

5.1. Total Quality Management

In the case study the approach to total quality management needed to be customised considerably (Figure 35). As processes and products vary fundamentally in Company A, competitive benchmarking could not be performed on a one-to-one level, as no sister site produced exactly the same products in exactly the same way. Adjustments were made to make a comparison meaningful and compare like with like. A quality management programme needs to take into consideration how to measure quality data in a way that makes it comparable without ignoring the individual features of the products. As processes varied for customised and engineered products, process capability measures could only be applied to repetitive processes such as the punching lines, since there were meaningful similarities.

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Formal continuous improvement programmes were implemented and led to tangible improvements. But the lack of repeatability of processes across the plant, made it necessary to make adjustments. Finding potential to improve is as likely in an engineer-to-order environment as in a serial production. However, the fact that repeatability is not given, the tools have to take into consideration that variability is prized. Visual Management and in particular 5s housekeeping may be even more important in an engineer-to-order organisation as variability defines that more options must be available leading to a bigger potential for disorganisation. However, the standards that are set for tools or processes must be flexible enough to support the variation in products. For Company A both 5s housekeeping, as well a visual management brought to the fore what was wrong and needed to be adjusted. It was the first step in identifying where waste was inherent. *Poka yoke* or error proofing was only possible for the processes that were repetitive.

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Total Quality Management and Visual Management – continuously improve and sustain quality	Competitive benchmarking	Customised	Customised	Customised	Customised	Customised	Customised
	Quality management programs	Customised	Customised	Customised	Customised	Customised	Customised
	Total quality management	Customised	Customised	Customised	Customised	Customised	Customised
	Process capability measurements	Customised	Customised	Customised	Customised	Customised	Customised
	Formal continuous improvement programme	Customised	Customised	Customised	Customised	Customised	Customised
	5s	Customised	Customised	Customised	Customised	Customised	Customised
	Poka Yoke				Customised		Customised
	Kaizen circles	Customised	Customised	Customised	Customised	Customised	Customised

Figure 35: Total Quality Bundle

5.2. Just-In-Time and Production Flow

For a just-in time approach, many adjustments had to be made to classical tools in order to fit Company A (Figure 36). It was not possible to reduce the lot sizes, as lot sizes were already very small and quantities were directly linked to customer orders. Continuous flow had to be customised to fit the production process. With lot sizes ranging between one to fifty pieces with an average of less than four pieces per order,

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flow in the classical sense was not suitable. The demand was smoothed in the sense that orders were timed in a way that the capacity could be utilised more evenly. Certain processes, such as the punching, could be levelled somewhat, as overall quantities were larger and variants were a slightly more limited. However, orders were scheduled to ensure as little waiting time as possible.

In an engineer-to-order operation, the processes are by definition organised based on a pull system, as nothing will be produced for which a customer order has not been received. Kanban only has limited application in a system based on such a high level of variety. It was useful for repetitive parts but could only be applied in a limited way for high variability processes. On the other hand, adapted cellular manufacturing proved to be quite beneficial for Company A, as the products are large and it is easier to move the operator around the product, with parts, tools and equipment close at hand. Cycle time reductions were hard to measure for processes that were not repeatable. For more repetitive functions, such as punching, cycle time reductions were meaningful and achieved. For non-repetitive process adjusted benchmarking was used to allow for comparison and therefore for improvement. Clearly, Company A was not a 'focused factory'. Producing for four business units with eleven different production lines forced the operation to make adjustments to be particularly well organised. But the plant will also always face the risk to quickly slip back into chaos. With such a broad offer of products to such a wide base of clientele, being well organised is particularly important. Bottleneck identification and removal was both necessary as well as implemented. It required a level of customisation as the variability also meant that the bottlenecks shifted depending on product mix. But in certain processes a clear bottleneck eventually was identified and consequently removed only moving the bottleneck to another work station. This was particularly evident in lines that experienced an increase in demand.

In an engineer-to-order environment, kitting is a very suitable tool, as it allows the preparation and delivery of required parts in accordance with the production orders. This saves a lot of time, movement and transportation, as operators can directly use the supplied parts in the manufacturing process. Company A introduced kitting across all production lines with much success and improved results. Any work in process control is difficult in an engineer-to-order environment. While this is important for any company to improve visibility, for Company A the very high mix of discrete products limited the possibilities. CONWIP was introduced in a limited way for punched parts.

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Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Just-in-time / Flow – flow and continuously removing waste	Lot size reductions		Not Applicable	Not Applicable	Not Applicable	Not Applicable	
	JIT/continuous flow production				Customised		
	Pull system/Kanban		Customised	Customised	Customised	Customised	
	Cellular manufacturing				Customised		
	Focused factory production systems				Not Applicable		
	Agile manufacturing strategies	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented
	Bottleneck/ constraint removal		Customised		Customised		
	Reengineered production processes	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented
	Takt time reduction	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented
	Cycle time reduction		Customised		Customised		
	Throughput		Customised		Customised		
	Kitting				Customised	Customised	
	CONWIP				Customised	Customised	
	Process improvements		Customised		Customised		
	Value Stream Mapping	Customised	Customised	Customised	Customised	Customised	
	Planning & scheduling strategies			Customised	Customised	Customised	
	Process capability measurements				Customised		
	Transportation reduction				Customised	Customised	
	Reduction in excessive movement				Customised	Customised	
	First pass yield (FPY)				Customised		
	Benchmarking		Customised	Customised	Customised	Customised	Customised

Figure 36: Just-in-Time/Flow Bundle

However, the kitting process proved to be overall more suitable. Process improvements were necessary and useful in this engineer-to-order arrangements.

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They needed to be adjusted to ensure that variability and flexibility remained part of the process. But they were an important tool with a big impact on reducing waste.

Value Stream Mapping was implemented in a limited way to identify waste and waiting time in the order placement process. It helped to remove some very obvious waste. But probably simple process mapping would also have led to the same result. Planning and scheduling strategies were very important to improve the overall company performance. But with the high number of discrete orders, customisation of scheduling and planning was inevitable.

For Company A, reducing transportation time allowed for major waste reduction. As the plant was large, the distances were long, and with the products being large and heavy, the effort that went into moving was tangible. Reducing transportation also improved overall safety. However, the large mix of products required a higher level of transportation than in a serial production, not least because kitted parts had to be delivered to the lines. Also, the reduction in overall movement helped reduce waste, as all required items were next to the work stations. However, to support the variability the number of tools and equipment was more than in a serial production. First pass yield is a measure that is more applicable to large volume production in particular in the process industry. This is a measure that is difficult to directly translate into an engineer-to-order environment, where the production is discrete. For company A it was only meaningful for the punching lines, where higher volumes were produced. More useful is the 'right first time' approach. An adapted approach to benchmarking was applied to the production processes, where adjusted comparisons were made with sister site. This did help to make improvements and reduce waste.

5.3. Human Resources Management

Mostly there is less requirement to adapt Lean practices in the human resources field, as people are people in an engineer-to-order as well as in a serial production environment. Consequently, for Company A, self-directed and multi-functional teams operated in the same way as for classical Lean practices. Equally, *gemba* walks and *asaichi,* or morning meetings, worked in much the same way as elsewhere. However, Lean teams needed to understand the need for flexibility and translate this into applying Lean practices in the engineer-to-order operation. The flexible, cross-functional workforce needed to have more skills, capabilities and experience, as the

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processes varied much more. The flexibility and adaptability requirements were higher than in serial productions. Consequently, also the job rotation required more training across a wider field for staff to be prepared to deal with variations.

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Human Resource Management – building the human resources as per needs of lean implementation)	Self-directed work teams	Regular	Regular	Regular	Regular	Regular	Regular
	Flexible, cross-functional workforce		Customised	Customised	Customised	Customised	Customised
	Lean teams	Customised	Customised	Customised	Customised	Customised	Customised
	Gemba walks	Regular	Regular	Regular	Regular	Regular	Regular
	Asaichi (morning markets on the shop floor)		Regular	Regular	Regular	Regular	Regular
	Multi-functional teams	Regular	Regular	Regular	Regular	Regular	Regular
	Job rotation	Regular	Customised	Customised	Customised	Customised	Customised

Figure 37: Human Resource Management Bundle

5.4. Total Productive Maintenance

For Company A, the implementation of preventive maintenance practices was the same as in a serial production setting. Maintenance was scheduled at regular intervals to ensure that breakdowns could be avoided. Critical spare parts were in stock, and machines were kept cleaned, and wear-and-tear parts were regularly exchanged. Company A had started a basic level of maintenance optimisation on the punching lines. A certain level of customisation of approach was required as the machines produce a considerable variety. So, collecting and evaluating relevant data is complex, and while this is a meaningful practice for mass production, in an engineer-to-order operation the effort required to keep this up may be more than the benefit that can be derived.

Safety improvements were high on the agenda of Company A. But with the large variety of heavy and bulky products, the approach to safety had to reflect the fact that processes and handling were not constant. Instructions were different for each production line but also had to account for variability within the lines.

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Company A also introduced new process equipment, especially where efficiency improvement and capacity gains could be implemented. But the variations in processes and products necessitated that the equipment allowed for flexibility. Similarly, the overall equipment effectiveness needed to be customised to a high-mix-low-volume requirement. Generally, overall equipment effectiveness is calculated using output. But an optimised output cannot be calculated if the parts, and therefore process time and output, changes regularly. But benchmarking with sister sites helped to bridge the gap. Quick changeover techniques could be applied in the classical Lean way and helped to substantially improve efficiency and increase capacity. Likewise, a level of autonomous maintenance could be implemented in the classical Lean approach, where regular machine maintenance was handled by operators, while strategic and major maintenance was conducted by the maintenance team. (See Figure 38)

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Total Productive Maintenance – maximisation of equipment effectiveness	Preventive maintenance				Regular		
	Predictive maintenance	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented	Not Implemented
	Maintenance optimization				Customised		
	Safety improvement programs	Customised	Customised	Customised	Customised	Customised	Customised
	New process equipment or technologies		Customised		Customised		
	Overall Equipment Efficiency				Customised		
	Single Minute Exchange of Dies, quick changeover techniques				Regular		
	Process capability measurement				Customised		Customised
	Separation of daily maintenance from strategic maintenance				Regular		

Figure 38: Total Productive Maintenance Bundle

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5.5. Standardisation

In a high-mix-low-volume environment standardisation is amongst the most difficult Lean bundles to implement. By definition high-mix-low-volume operations thrive on variability and flexibility. This contrasts with standardisation and removal of variation in a classical sense (Figure 39). However, an adjusted level of customisation was very useful for Company A. It helped to structure and streamline processes and forced the operation to evaluate the status quo, often to find that efficiency and effectiveness could be improved. While procedures existed, they had not been updated in a long time and reality had overtaken them.

Company A did organise its operation by product family and size. However, even within the product families, a considerable level of customisation and engineering still existed. While it was possible to improve the organisation by further breaking them down into categories within the existing product lines, there was a limit to how much uniformity and repetitiveness was possible without diminishing the customer value offering.

One approach was to evaluate modularisation potential. For one sub-category of Product 3, this was possible and implemented. For some product lines, it was also possible to modularise some part families. However, while it was certainly helpful, the business model of Company A required an unavoidable and relatively high level of customisation and engineering.

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Standardisation (STD)	Standardising processes and procedures	Regular	Customised	Customised	Customised	Customised	Customised
	Modularisation		Customised		Customised	Customised	
	Product families by size		Customised	Customised	Customised	Customised	Customised
	Written procedures	Regular	Regular	Regular	Customised	Regular	Regular

Figure 39: Standardisation Bundle

Company A boasted written procedures across all functions, including written work instructions, for the Production Department. But with the two major layoffs many

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processes were by necessity adjusted and rearranged. However, the written procedures had not been updated to reflect the new realities on the ground. As routings changed with each order, the work instructions needed to be customised to allow for sufficient flexibility in processes to account for product variations. Step-by-step, all work instructions were updated and this process did support the overall improvement in performance.

5.6. Lean Purchasing

Lean purchasing is another area where customisation of Lean practices was necessary (Figure 40). With discrete and highly specialised part requirements, finding sufficient interested suppliers was already challenging for Company A. The relatively tight specifications coupled with a low volume and pressure on lead times, diminished the potential supplier base. Reducing the purchase order size was mostly not possible, as part orders were based on committed customer orders, and total quantities were already small. This would have also made deliveries highly inefficient. What did help to reduce waste, was to consolidate shipments, where a truck would pick up parts from several suppliers and then deliver the parts together to Company A. Of course, this required a considerable level of organisation and was consequently only introduced in a second step.

To allow for a shorter order placement process, Company A committed to reserving a certain amount of capacity at critical suppliers. This allowed lead times to be optimised and also provided suppliers with certainty. It also helped to shorten lead times for customers.

The closer relationships with critical suppliers did help Company A in reducing incoming inspection of material and parts. However, the extensive variation in parts requirements made a certain level of incoming inspection an unavoidable necessity. However, categorising parts into groups made it possible to take a structured approach to the incoming inspection of parts, effectively reducing the volume of parts to be individually checked.

Long term purchase agreements were beneficial for both Company A as well as its suppliers. The commitment from Company A encouraged suppliers to dedicate resources in terms of highly skilled staff, capacity, investment in specialised

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machinery and shop floor area dedicated to the production of parts for Company A. It also encouraged the reduction in lead times. However, as forecasting is difficult for Company A, the agreements had to remain relatively flexible.

Implementation of Kanban in Company A did exist for common parts. But the large mix of products, parts and materials made this approach limited. For company A, kitting was the more suitable approach to reduce work in process and material being stacked near or in production lines.

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Lean purchasing (LP)	Reduced purchase order sizes					Not Applicable	
	Short order placement processes					Customised	
	Reduced need for incoming material inspection						Customised
	Long-term purchasing commitments					Customised	
	Kanban boxes for common parts					Customised	
	Kanban for replenishing					Customised	

Figure 40: Lean Purchasing Bundle

5.7. Supplier Involvement and Development

At the start of the Lean restructuring programme, supplier on-time delivery was very poor causing delays and production rescheduling. So, improving supplier relationships was critical. Company A put considerable effort and time in improved communication and clarity of message. While the approach does not differ from a classical Lean approach, the sheer volume of variety probably makes this Lean practice even more important in an engineer-to-order company than in a mass production setting, where an operation has considerable leverage over suppliers (Figure 41). Providing regular feedback to suppliers on key performance measures highlighted to suppliers what was critical to Company A and could therefore be

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improved. The increased visibility for suppliers made it possible for them to commit to improved quality, on-time delivery, lead time and prices.

As many parts procured by Company A were based on a single source strategy, it was a matter of urgency to find new suppliers that could be developed. The large quantity of parts made a customised approach necessary. Overall more suppliers were required, while at the same time many suppliers were not interested in the complex part demands. Company A had an audit and certification procedure in place, which did not differ from classical Lean approach.

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Supplier Involvement & Development (SID)	Close contact and long-term relationship		Regular	Regular	Regular	Regular	Regular
	Supplier feedback					Regular	Regular
	Improvement commitments from suppliers					Regular	Regular
	Supplier development and certification					Customised	Customised
	Supplier audits & certification					Regular	Regular
	Lead time improvements		Customised	Customised		Customised	Customised
	Quality improvement commitments		Customised			Customised	Customised

Figure 41: Supplier Involvement & Development Bundle

5.8. Customer Involvement and Partnership

Of course, to ensure that Company A's operation could fulfil the customer value offering, it was imperative to understand customer needs. As each customer's requirements were so specific, a customised approach to the customer relationship was necessary (Figure 42). Moreover, as the products were complex and the level of customisation and engineering very high, only with very close collaboration and communication could it be ensured that customer wishes were reflected adequately in the product. This communication process had to start early in the process, in line with the order penetration point. In the case of Company A, customer feedback also

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needed to be geared toward the specific customer requirements to reflect the highly individualised offering.

Lean Practice Bundle	Practices	Human Resources Department	Engineering & Design Department	Project Management & Order Execution Department	Production Department	Supply Chain Management Department	Quality Department
Customer involvement and partnership (CIP)	Customers' direct engagement in product offerings		Customised	Customised	Customised		Customised
	Customers' feedback on different performances		Customised	Customised	Customised	Customised	Customised

Figure 42: Customer Involvement and Partnership

In summary, it can be said that for Company A it was possible to implement most of the Lean practices. Many had to be customized to the company's specific needs and only a few did not find application. Implementing Lean practices did lead to tangible performance improvements. Notably, the Lean bundles contained both soft as well as hard practices and were focused on both internal as well as external processes. Furthermore, practices were implemented as a holistic system with a view to sustaining the gains.

Finally, in Company A, implemented as a whole system, the adapted Lean practices still led to the anticipated goal of reduced waste, better smoothing and less overburdening. The further the Lean restructuring programme progressed, the more tangible the goal of less overburdened staff and machines became, and the more the processes became levelled, and the more the overall waste was reduced.

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6. Conclusion

This study asked the question of whether Lean practices find applicability in an engineer-to-order environment in the same way as in a mass production or in low-mix-high-volume environments. Furthermore, it looked to explore whether Lean practices can be implemented in the classical way in an engineer-to-order operation or whether adaptations to Lean practices are necessary.

The study showed that for Company A the implementation of Lean practices in a holistic and integrative way across the organisation has led to tangible performance improvements. The Lean practices were adapted to suit the requirements of Company A. A considerable level of customisation was required to adjust classical Lean practices to fit the more flexible and dynamic needs of company A. The Lean practices were implemented both externally with customers and suppliers, as well as internally within the organisation. Soft practices relating to staff and communication with external parties were implemented in conjunction with hard practices in the sense of Lean tools on the shop floor and across processes.

In line with Lean philosophy expectations, the Lean restructuring programme did considerably reduce waste (*muda*) across the organisation and allow for a better production flow through smoothing of demand (*mura*), in turn reducing the overburdening of staff and of equipment (*muri*). It can therefore be concluded that the implementation of Lean practices can also lead to performance improvements in the more dynamic and less stable environment of engineer-to-order companies.

The study's limitation is that the research was only conducted on one single case study. Therefore, the findings may not be entirely generalisable, where other engineer-to-order companies producing different products and operating under different conditions may require a different approach. Also, the customisation of Lean practices may conceivably require customisation of different practices with a different focus.

With the considerable differences that exist in manufacturing processes in general, it may be expected that a certain level of customisation will always be required, where companies need to evaluate what fits their particular setup. Undoubtedly Lean

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practices can lead to considerable performance improvements and should consequently be considered in modern operations.

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8. List of Abbreviations

B2C – Business to Consumer

CONWIP – constant work in process

HVAC – heating, ventilation and air conditioning

JIT – Just in Time

POLCA – Paired-Cell Overlapping Loops of Cards with Authorisation

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