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MASTERARBEIT

Material Flow Planning of Assembly Lines With Emphasis on Parts Supply –
Formulation of a Lean Methodology

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Deutsche Kurzfassung

Die vorliegende Arbeit zielt auf die Abfassung einer Methode zur Materialflussplanung von Montagelinien ab, die als praktische Anleitung benutzt werden kann. Eine Literaturrecherche hat auf eine methodische Lücke in diesem Bereich hingewiesen: während es viele Publikationen über Materialflussprinzipien (z. B. Push/Pull, Kanban, usw.) gibt, mangelt es an konkreten Beschreibungen von Vorgehensweisen zur Materialflussplanung und Ausgestaltung von Versorgungsstrukturen. Die Arbeit versucht diese Lücke durch Formulierung einer solchen Methode zu füllen. Als thematisches Fundament wurde Lean Manufacturing gewählt, da dies am besten geeignet erschien, um die hohen, vielseitigen und teilweise widersprüchlichen Anforderungen der heutigen Märkte zu erfüllen.

Im ersten, theoretischen Teil werden traditionelle und moderne Prinzipien der Materialflussgestaltung besprochen. Lean Production Grundlagen werden präsentiert, gefolgt von detaillierten Beschreibungen einzelner Methoden, die während der Planung eingesetzt werden, wie Wertstromanalyse, Eliminierung von Verschwendungen, Materialflussprinzipien, Kanban. Im nächsten Kapitel werden die wichtigsten zu beachtenden Einflussfaktoren der Planung betrachtet, die anschließend zur Bewertung der im nachfolgenden Literaturüberblick vorgeführten Planungsmethoden herangezogen werden. Im praktischen Teil werden erst Ziele, Annahmen, Abgrenzung und Struktur der neuen Planungsmethode diskutiert und dann die Methode erklärt. Ein phasenbasiertes Vorgehen wird angewandt, das sich „flussaufwärts“ entlang dem Materialstrom orientiert, von den Kundenanforderungen und –bedarfen an die Produkte, über Ausgangslager, die Montagelinien bis zur Materialversorgung zum Eingangslager. Alle Schritte werden ausführlich beschrieben und weiterführende Literatur aufgezeigt.

Abstract

This thesis aims at providing a method for planning the material flow of assembly lines that can be used in practice. A literature review brought to attention a gap in this area: while there are many material flow techniques such as push/pull or kanban, there are few planning methods available. The paper attempts to fill this gap by formulating such a planning process. Lean management was chosen as the method foundation, as it seems the most adequate in fulfilling the high, multi-faceted and partly conflicting requirements of today's markets.

The first, theoretical part introduces and contrasts conventional and modern material flow principles. Lean manufacturing is introduced, and the techniques that will be used in the planning method are examined more closely, from the plan for every part, through value stream analysis, identification of wastes, material flow parameters, types of flow to principles of kanbans, supermarkets and purchased parts markets. The next chapter summarises the most important factors and objectives to consider during planning, which are then used in the following literature review, where several planning methods are introduced and evaluated. In the practical section, the basic goals, assumptions and structure of the planning method are first discussed and then the method itself is formulated. The method is divided into phases which travel upwards along the value stream, from the customers and the demand on products through finished parts stock, assembly lines, up to the material supply and purchased parts market. All steps are thoroughly described and documented and further information in the literature is referenced.

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Abbreviations

ABC.................... Activity-Based Costing or the 3 categories in an ABC-Analysis
AD...................... Average Demand
ADU................... Average Daily Usage = *AD* for one day
APS .... Advanced Planning and Scheduling
BI .... Buffer Inventory
BOM .... Bill of Materials
CONWIP............ Constant Work in Progress
CQ...................... Container Quantity
CT .... Cycle Time
DfA..................... Design for Assembly
DOH .... Days on Hand
EPEI .... Every Product Every Interval
FIFO .... First In First Out
HMLV .... High Mix Low Volume
JIS .... Just in Sequence
JIT...................... Just in Time
LT....................... Lead Time
MRP................... Material Requirements Planning
NVA.................... Non-value-adding
OPT.................... Optimized Production Technology
PAC.................... Production Authorization Cards
PFEP .... Plan for Every Part
PTP .... Pull Trigger Point
QFD................... Quality Function Deployment
RT .... Replenishment Time
SCQ.................... Standard Container Quantity
SD .... Standard Deviation of Demand
SMED .... Single Minute Exchange of Die
SPC .... Statistical Process Control
StdDev or STD... Standard Deviation
TCT .... Total Cycle Time
TOC .... Theory of Constraints
TPM .... Total Productive Maintenance / Management
TQM................... Total Quality Management
TPS .... Toyota Production System
VSM .... Value Stream Mapping
WIP .... Work in Progress / Work in Process
Z......................... Z Value

Chapter 1 – Introduction

1.1 Motivation

As a student of industrial engineering and a creative person, the whole process of creating products based on customer needs has fascinated me, including all the steps from design through manufacture to assembly. The thinking in processes and improvement of these seems a very positive notion, which is especially interesting in the inner workings of a producing company, hence the thesis topic. While the original topic proposed was the supply planning of assembly lines, the research of literature has led to the conclusion that a more thorough approach would be more effective, encompassing the material flow to the assembly line and inside the line, while also considering the parallel activities of assembly line planning.

1.2 Background

Manufacturing companies are faced today with a multitude of difficulties, not only does the global marketplace require customized products, near perfect quality and quick shipments to keep the customer base, but enterprises are placed under a growing pressure to cut costs and increase efficiency and therefore the return. These have only been augmented by the recent global economic crisis.

Assembly lines in particular are the operations most close to the customers and therefore feel the pressure of high requirements the most. As the market has become ever more customer-oriented, going from push to pull, the traditional mass production has become history. Just some of the requirements on assembly today are the production of many varieties in small batches, short product lifecycles, deliveries increasingly expected to be delivered just in time, without defects, while reducing the costs of assembly. Conventional methods of push, batch-and-queue and highly specialized machinery cannot compete, instead, methods for shortening lead times, minimizing inventory and reducing lot sizes are required.

The material supply to the line and the material flow inside the line are among the key factors in reaching the goals of flexibility, just in time delivery and quality while reducing costs. While small changes and optimisations can be made to an existing assembly line to a certain extent, meeting the high aforementioned goals requires a replanning of the whole assembly line, an important part of which is planning the supply and material flow, which is the topic of this paper.

1.3 Objectives

The first goal of this thesis is to review the literature for any existing planning methods and to evaluate these: to what extent do they cover the thesis' area of focus and to what extent do they provide the means for reaching the aforementioned requirements? A manufacturing system that seems adequate to reach these goals is lean manufacturing (aka. Toyota Production System), whose benefits until now have been far from exploited, though it has been known and discussed in the Western literature for some time. While there is much informative literature on specific subjects, step-by-step planning or implementation guides are few and lacking.

This thesis endeavours to fill this gap and formulate such a guide for planning the material flows in an assembly line, laying an emphasis on the material supply. The target audience includes small to mid-sized manufacturing firms, especially those starting on the path to a lean and efficient assembly line.

1.4 Methodology

There are two main parts to this thesis, a theoretical and a practical section. Chapter 2 contains all the theoretical groundwork for the rest of the thesis. First, traditional methods of push-based material supply are described and evaluated, followed by an introduction to lean, whose principles are shortly described and contrasted with the push-based methods. A "Lean Toolbox" is given, showing the many possibilities of improving an assembly line or the whole manufacturing operations. The following parts of the chapter describe those lean concepts and tools in more detail which will be used during material flow planning.

As the first part of the practical section, Chapter 3 introduces the factors that influence material flow planning, including physical and non-physical factors, as well as often used criteria in classification methods. Then the goals that are to be met are examined.

Chapter 4 follows with a literature review, examining a number of methods. The core idea and the main steps of each are described, as well as how well they cover the chapter 3 factors and how relevant they are to the thesis topic. At the end a short evaluation of each is given and the best four are selected, whereby none of them cover the thesis topic and all of the factors exactly.

Based on the findings of chapter 4, a new planning method needs to be formulated, which is presented in Chapter 5. The first section introduces the central idea of the new method, any assumptions that are made and definition of its scope. This is followed by an overview of the whole method, while the rest of chapter five details the planning phases. The structure is based on the five phases of lean, and follows the core idea of planning upwards along the value stream. Starting from customer demand, through the finished-parts market, the assembly line, up to the material supply and the purchased parts market. Throughout the planning method, references are made to planning activities that fall outside the scope but should be done parallel with material flow planning, including assembly line planning, transportation planning, warehouse planning, etc. A number of sources are referenced to support the method and to give further, more detailed information on particular planning steps.

Chapter 2 – Theoretical Groundwork

Before elaborating on the planning methods available in the literature in Chapter 4 and the synthesis of a new material flow planning methodology in Chapter 5, the theoretical groundwork must be laid. This chapter focuses on material supply methods as well as other principles and tools that will later be needed in the thesis. *Section 2.1* shortly overviews the "classical" methods and their shortcomings. *Section 2.2* then introduces lean, which is used later in chapter five to build the new planning method. The rest of the sections describe various lean and other modern methods grouped according to the five stages of lean implementation.

2.1 "Classical" Methods

2.1.1 Push Principle

The push principle means that each unit in production produces to a predetermined schedule irrespective of the following or preceding processes, i.e.: the orders are "pushed through the system". It lays the finished parts into a buffer after it, and takes new parts from the buffer before it. The buffers between steps usually contain enough material to supply the next process for days. This is the traditional type of material flow, still used in many companies. It requires a centralized planning of the orders ("*scheduling*") and control of production.

2.1.2 Batch and Queue

A central paradigm closely related to the push principle, but much more universal in nature is the thinking in "batches and queues." This is the central conviction that in order to produce efficiently, one needs to divide everything into different *functions* and *departments*. Then to use efficiencies of scale, like orders need to be grouped together into large batches and processed at once, while the other products wait.[1] So to produce a given quantity of a product, the idea is to do the first step on all the parts, then transfer them to the next process and do step 2 on each and so on. If there are three products: A, B and C with about equal demands, then produce a bunch of A, for example for 2 weeks, then change over to product B for two weeks, then to C and then repeat. To satisfy demand in the meantime, at least 6 weeks of stock is needed for each product, or the customer needs to wait.

[1] Womack and Jones, 2003, p. 21.

2.1.3 Material Requirements Planning Based Methods

To be able to give the processes their separate orders according to the push principle, production planning needs to take place in advance. This happens today almost exclusively with computer software. The basic method, independent of software system used:

- Try to forecast the number of orders in the future (sales forecast), planning these for several months ahead.
- Calculate the primary, secondary, tertiary material and parts requirements using “exploded” Bills of Materials.
- Then, using backwards scheduling from the order date, using the predetermined lead time (process times + queue times) and safety margins,
- in more advanced systems also taking the available capacities into account,
- produce the production plan.

The most widespread are the so called MRP-based methods. *Material Requirements Planning* (*MRP I*) was originally a system that used the Bill of Materials and scheduling rules to produce the production schedule. This was then expanded with capacity planning and production control in *MRP II* (*Manufacturing Resource Planning*). The *Enterprise Resource Planning* (*ERP*) systems in use today also use MRP II principles for production scheduling, while expanding it with a number of modules to cover most activities in a company. The result is a sophisticated, but highly complex system that also requires a high investment to install and run. One author adds:

> *“Another trap that the software suppliers have fallen into in the race to provide increased functionality is to add complexity to the configuration process. This has resulted in many horror stories of incorrect configuration, and a demand for highly skilled "configurers" which for a time outstripped supply. These factors combined to constrain sales of the software, and has led to the sale of preconfigured or cut down versions of complex software. Unfortunately this misses the point which is that the manufacturing plant was simply trying to plan materials and capacity* ***simply****.”*[2]

2.1.4 Other Push Methods

Drum, Buffer, Rope (Theory of Constraints[3])

The Theory of Constraints focuses on finding the bottlenecks in the company. Since the whole system runs as fast as its slowest part (the bottleneck), this bottleneck should be scheduled, while the rest of the system is made to keep up with it. The three main material flow related elements of this method:

[2] SM Thacker & Associates: Materials Management & Stock Control, 2009 (emphasis in original).
[3] See: Goldratt, E. M. and J. Cox: The Goal: A Process of Ongoing Improvement, North River Press, New York 1986.

- *"The 'Drum' is the schedule for the bottleneck (drumbeat for the whole system).*
- *The 'Buffer' is surplus stock put in front of the bottleneck to make sure it never runs out.*
- *The "Rope" is the coupling mechanism for ensuring that inputs (release of raw materials) do not exceed the bottleneck capacity, avoiding build-ups of unnecessary WIP."*[4]

While the schedule is push-based, the rope can also function along the lines of the pull principle (see *Section 2.7*) in Lean Management.

OPT (Optimized Production Technology) and APS (Advanced Planning and Scheduling)

Based on the Theory of Constraints, OPT and its successor APS are its software implementations. OPT used a closed-source algorithm, while there are different APS systems, partly with open algorithms. This type is characterized by the following:

- *"Sophisticated, (some would use the word complex)*
- *A computer based modelling system which is principally based on Bill of Materials, Routing, & Costs, but can be based on more complex scheduling rules*
- *Uses critical path networking or optimisation routines*
- ***Anti-Lean****"*[5]

While very sophisticated algorithms can produce very precise results, they can be "precisely wrong" in practice. For one, it is extremely hard to accurately model of the complexities and uncertainties of reality. In practice, the software usually needs a specialist to implement, the reason for the resulting work orders cannot be understood (black box) and therefore feels forced on the employees, all the while the system needs extensive administration of data.

2.1.5 Disadvantages of Push and Batch and Queue

The batch and queue thinking has led to ever larger machines to process ever larger batches, as quickly as possible. The large machines led to long changeover times, which needed to be kept to a minimum, therefore enforcing the need for larger batches, leading to more inventory pile-up, all in a positive feedback loop. The functional grouping of machines and workstation created chaotic material flows, with a lot of transportation and even more inventory.[6] The large, expensive machines also had to produce non-stop to bring the proper return on investment, which meant a large supply buffer was needed. Although the machines are seemingly producing very fast, any given product has a long lead time and the large inventory has other negative effects.

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[4] SM Thacker & Associates: Materials Management & Stock Control, 2009.
[5] Ibid. (emphasis in original).
[6] Lee, 2007, p. 15.

Possible disadvantages using a push-based material flow:

- Long lead times caused by long queue times with short value producing production times and all the results of this: low consumer satisfaction, overproduction, etc.
- Quality and other problems are only discovered late.
- Large stocks and works-in-process, leading to high capital binding.
- Large capacities are used for non-value-adding activities, many indirect workers (in sales, controlling, finance, PPC, etc.) and an unusually large and superfluous IT department (including costs of hardware, software, personnel and support OR the costs of outsourcing the whole thing.)
- Bullwhip-effect,[7] snowball-effect and others.
- Small problems or disturbances on the shop floor make the "perfect" production plan unusable, they lead to machine stops, "firefighting" to bring critical orders through the system, whereby they delay other orders, and so on.
- Increasing complexity of the systems, no transparency of how the results are achieved, just a "black-box".
- Another problem being that these software systems only imitate reality, they cannot make changes or improvements.

When to use?
Scheduling systems are however far from useless. Even in case of pull-based material flows, a long-term planning based on demand forecasts is required. A "mixed-mode" operation is possible using MRP for long-term capacity planning, while using just-in-time pull methods in day-to-day operations.

2.2 Lean Basics

Lean is an unending journey to be the most innovative, most effective and efficient organization. The Power and Magic of Lean is to continually discover the hidden opportunities existing all around you.[8]

— Norman Bodek (published the works of Dr. Shigeo Shingo and Taiichi Ohno)

2.2.1 A few words on history

A fundamentally different concept to the conventional methods of push or batch and queue is **Lean,**[9] which burst into the Western world in the nineties, following the publication of Womack, Jones and Roos' book: "*The Machine that Changed the World*", which endeavoured to explain the unparalleled progress and success of certain Japanese firms, above all Toyota.

[7] Bullwhip-effect: fluctuations in demand amplify upwards along the value stream.
[8] Strategos Inc.: Pioneers of Lean Manufacturing — Taiichi Ohno & Shigeo Shingo, p. 2.
[9] *Lean* (or Lean Manufacturing) and Toyota Production System (TPS) are usually treated as synonyms in the literature, although some authors point out minor differences. Just in Time (JIT) is mostly described as one of the basic principles of lean, while rarely JIT is also used as a synonym of the whole system. This thesis will use the phrase *lean*.

The underlying philosophy and its concrete techniques had been developed at Toyota around the middle of the 20th century, its most prominent originators being Taiichi Ohno, Assembly Shop Manager and later Vice-President of Toyota and his mentor Dr. Shigeo Shingo, who led a consulting firm. Together they created the methods known today as SMED, SPC, Poka-yoke, JIT, Kanban and others, to solve the concrete problems facing Toyota in particular and Japanese manufacturing in general at the time.

2.2.2 Main Elements

No attempt will be made here for a short and concise definition of lean, as there are so many different views and points of focus in the literature. What can be said however, is that Lean is a comprehensive manufacturing or management philosophy, centered around the following main elements, which are also the five stages of lean implementation:[10]

1. Value: value is defined only by the customer, always expressed in terms of a specific product.

2. Value Stream: the value stream of a product is identified and wastes are found and eliminated. Every non-value adding activity classifies as waste. One especially important class of waste is inventory. Some sources go so far as to say that the point of lean is minimising inventory; while this is one aspect, there are others. The value stream must be analysed as a whole and improved.

3. Flow: the opposite of batch-and-queue. Instead of building a function-based organisation with large and fast machines and having mountains of inventory between steps, lean focuses on the products. These need to be made to *flow* without stopping through all processes along the value stream. This means right-sizing equipment, eliminating wastes, shortening changeover times.

4. Pull: instead of pushing products onto the customers, they can *pull* the exact product they need. This is applied to all steps along the value stream: everything is produced if and only if the next process needs it, exactly when it needs it, that is, just-in-time. Instead of centrally calculating and scheduling all processes, only one process is scheduled ("*single point scheduling*") and this pulls the processes before it.

5. Perfection: constant improvement is promoted towards the long-term vision of "perfection". See figure below for an example "ideal" factory.

[10] See: Womack and Jones, 2003.

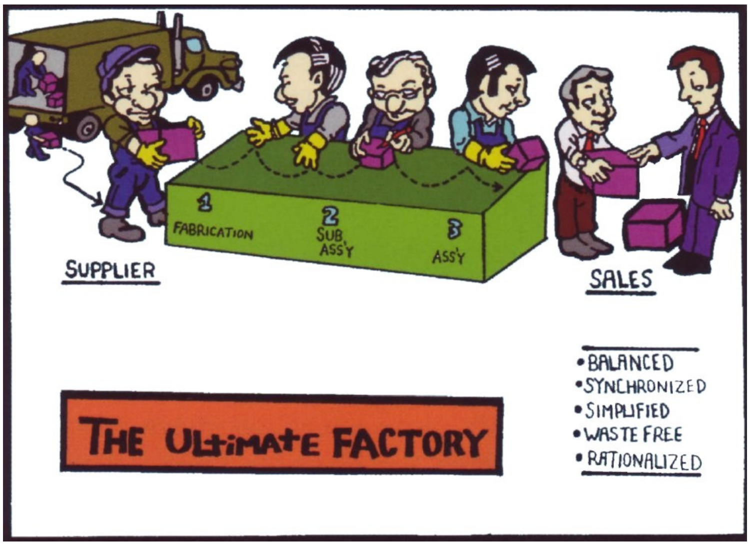

Figure 1: An ideal factory, with unobstructed single piece flow from suppliers to customers.[11]

Goals of Lean Manufacturing

Correctly specifying *value*, analysing and removing wastes from the *value stream*, making products *flow*, letting them be *pulled* from the downstream processes and *continuously improving* the system leads to immense improvements of many metrics, some of which are traditionally thought to be contradictory. Lead time, effort and space required to manufacture a product are greatly reduced, while quality approaches 100%, costs are reduced and employee morale is increased **at the same time**.

2.2.3 The "Lean Toolbox"

In order to implement the main elements and reach the goals of lean, a number of methods have been developed for specific problems. It is important to note that it is not "lean" to pick a collection of tools from the lean toolbox or copy others' techniques, but to follow the central thinking. Which tools to use then depends on an analysis of the given situation. The following is a non-complete list of elements in the "lean toolbox" that can be useful in given situations.[12] As Spear and Bowen put it:

> *"Toyota does not consider any of the tools or practices – such as kanbans or andon cords, which so many outsiders have copied – as fundamental to the Toyota Production System. Toyota uses them merely as temporary responses to specific problems that will serve until a better approach is found or conditions change. They're referred to as "countermeasures," rather than "solutions"..."*[13]

[11] Source: Lee, 2007, p. 15.
[12] For a more comprehensive list, see: The Northwest Lean Networks: Lean Terms & Definitions, 2009 and Lean Business Systems: Lean Toolkit, 2009.
[13] Spear and Bowen, 1999, p. 104.

LEAN TOOLBOX	
5S	"Industrial housekeeping" to keep the workplace organised, clean and efficient, comprised of the following 5 steps: *Seiri* (Sort), *Seiton* (Set in Order), *Seiso* (Shine), *Seiketsu* (Standardize) and *Shitsuke* (Sustain).
7 Wastes	Taiichi Ohno defined 7 categories of waste ("*muda*"), which should be found and resolved: Overproduction, Movement of Material, Motion, Waiting, Inventory, Unnecessary Processing, Defects and Correction. Womack & Jones added an eighth: Bad Design, another one mentioned frequently is Underutilisation of the Employees' Talents.
Cells / cellular manufacturing	Cell based production/assembly lines facilitate flow, improve efficiency and productivity while working with less waste.
Gemba	Effective solutions cannot be made in the office, one must go to the "real thing" (*gemba*), that is, the shop floor.
DfM, DfA	Design for Manufacture, Design for Assembly.
Heijunka	A method for leveling production to heighten flexibility and reduce the "bullwhip effect".
Hoshin Planning	Also called *Policy Deployment* or *Strategy Deployment,* a method for determining what to do and how to do it, to reach the company's strategic goals.
Jidoka / Autonomation	"Intelligent" mistake proofing built into the production machinery, so that no defects are built or passed on.
Just-in-Time	The philosophy of making only what is needed, when it is needed, in the amount needed. The customer can be the end customer or the next in-house process.
Just-in-Sequence	Extension of JIT to supply parts in the production sequence of the customer process.
Kaikaku	Radical change / reengineering.
Kaizen	Continuous, incremental improvement, usually in form of kaizen workshops.
Kanban Pull	A material handling system for achieving pull, based on the customer signalling what it needs in which quantity.
PFEP	A Plan for Every Part database contains a number of vital information for every single part used in the factory, and is the base of many decisions concerning the material flow.
Poka-yoke	Mistake proofing device, procedure or feature to prevent defects.
Quality Function Deployment	A structured method used to identify customer needs and translate them into specific product features.
Root Cause Analysis	Ishakawa diagram (fishbone diagram), 5-Whys and other tools to find the root causes of a problem and therefore enable a solution of the cause, not the effect.
Six Sigma	A statistical analysis and improvement method originated at Motorola, also used in lean.
SMED	Single Minute Exchange of Die, a method for quick setups and changeovers.
SPC	Statistical Process Control: monitoring a process through control charts.
Standard Work	An agreed upon best-practice, used as work instructions.
TPM	Total Productive Maintenance (or Management), a method related to and often used with lean.
TQM	Total Quality Management, a method related to and often used with lean.
Value Stream Mapping (VSM)	A method for mapping the material and information flows of a factory using standard symbols, used extensively to support lean projects.
Visual Techniques	Using visual tools to monitor processes, making them transparent and problems easy to spot. Examples are production boards, heijunka boxes, etc.
Work Balancing	Balancing the work contents of operators to be ≈ takt time.
Lats but not least "Just do it!"	This is no tool or technique, but an essential message of lean: "Stop waiting, do not explain away the problems or push the responsibility on others, just go and do it!" Do go to the shop floor, do get your hands dirty, do improve the system, do get rid of waste.

Table 1: Lean Toolbox (own compilation, with no claim of completeness)

In the following, specific methods that will be used during the material flow planning of assembly lines will be examined. The structure of the following sections is based on the five phases of a lean implementation project, each method is introduced in the relevant phase.

2.3 Starting a Lean Project

Lean lays a big emphasis on the involvement of employees, and that all change should be more "worker pull" rather than a big "management push."[14] The people who are most familiar with the processes are able to do the most, and their active involvement will boost their motivation through recognition of their abilities. Since the project will not happen from its own, active management direction and guidance is needed, as well as constant feedback and two-way dialogue between layers of management and employees.

If you don't trust the people, you make them untrustworthy
— Tao Te Ching[15]

The basic practice is as in modern project management: first a project team is formed: management must choose the project leader[16] and the core team members. Cross-functionality should be observed, having someone from *Human Resources* helps because a lean transformation will lead to redefining / reclassifying jobs; an employee from *Finance* will help in the economic aspects and necessary funds for changes, and so on. The leader should possess a sense of ownership for the product and commitment to lean, with the necessary authority:

> "*A Value Stream Manager is a person that is responsible for increasing the ratio of value to non-value, and eliminating waste in the overall supply chain from start to finish, for a defined product family; and for ensuring that the value stream meets or exceeds customer requirements*." [17]

At the start of work, a kick-off meeting should be held to inform all the members how and why the team was assembled, what needs to be planned, and a review of lean tools needed. Finally, the team and the leaders must physically go to the shop floor and observe production/assembly and address the problems there.

As a comparison, the first steps of the project are proposed by Carl Wright in his twenty step lean implementation in the following way:

[14] For more, see Tapping, Luyster, Shuker, 2002, from p. 13.
[15] Tao Te Ching, http://www.wayist.org/ttc%20compared/chap17.htm
[16] Often called a "Champion" in lean terminology.
[17] Lean Enterprise Institute: The Value Stream Manager, 2004, p. 1.

1. *"Form team (mix of lean manufacturing and relevant business experience)*
2. *Develop communication and feedback channel for everyone*
3. *Meet with everyone and explain the initiative*
4. *Begin to train all employees (lean overview, 8 wastes, standard operations, kaizen, RCPS, PDCA)*
5. *Facility Analysis - Determine the gap between current state and a state of "lean"*
6. *5S - It is the foundation of lean. Workplace organization is critical for any lean initiative*
7. *TPM - begin total productive maintenance early (used throughout lean)"*[18]

From these the first four steps are part of the *Preparation Phase* of the new method in *Section 5.3*. The fifth step comes then in *Phase 2*, when the current state of assembly is mapped and analysed. The steps 6 and 7, that is the introduction of 5S[19] and TPM tools as foundations of lean are less clear cut. These can be a good idea to start, several sources say that 5S should be implemented at the start to "clean up the factory". On the contrary, Lee points out a common pitfall often seen in practice:[20] just picking a bunch of tools from the lean toolbox and applying them without thought. Lean should not be a "cookie-cutter approach", but a solution tailored to the company's needs. TPM might be needed or it might not be needed, an example for the latter being a pure assembly operation with few machines. He argues on[21] that although many companies hold 5S to be a good starting point, the redesign into work cells first and 5S only later is a better approach. Reasons being: for one, the return on 5S is lower, comes later and is less obvious. Second, the redesign of the assembly line means most of the 5S work must be done all over again, which is a waste of resources. In any case, the project team must decide which measures to take under the given circumstances.

2.4 Lean Phase 1: VALUE

2.4.1 Specifying the Value

The first step in a lean project is to specify the value, where the value is defined by and only by the customer. It is something that gives the user a specific functionality or benefit, always understood in terms of a finished product.[22] In the case of (re)planning an assembly line, it is important to reflect on the products the company produces or plans on producing and also make necessary changes to the company organisation.

[18] Wright, 2009.
[19] 5S is a method for keeping a workplace in order and clean, for more details see for example: Lean Business Systems: Lean Toolkit, 2009.
[20] Lee, 2007, p. 14.
[21] Ibid., p. 17.
[22] Womack & Jones, 2003, p. 16.

There are a number of modern methods for transforming customer needs into products, such as *Voice of the Customer*[23] or *Quality Function Deployment*[24] (QFD), these are separate fields of research in themselves. The basic idea in all of these is to involve the customers in the planning process as much as possible. The traditional, engineer-centered view of development needs to be replaced by a completely different viewpoint: instead of selling customers a clock or a drill machine, the right product to sell is actually "*a way to tell the time*" or "*a hole in the wall.*"

2.4.2 Product Based Organisation

For the transformation of a manufacturing company into an efficient and productive business, many authors suggest "segmenting" the organisation. The lean method is based on segmentation according to products or product groups. Instead of having vertically separated departments in the company pyramid, groups running horizontally across all departments should be created, where each group is responsible for one product family.[25] These are also known as *units*, *business units*, or *profit centers*.[26] The routes of communication and responsibilities are then not bound by the "invisible walls" between departments, but can *flow* from the inbound to the outbound side, efficiently creating value. A flatter and wider hierarchy also helps.

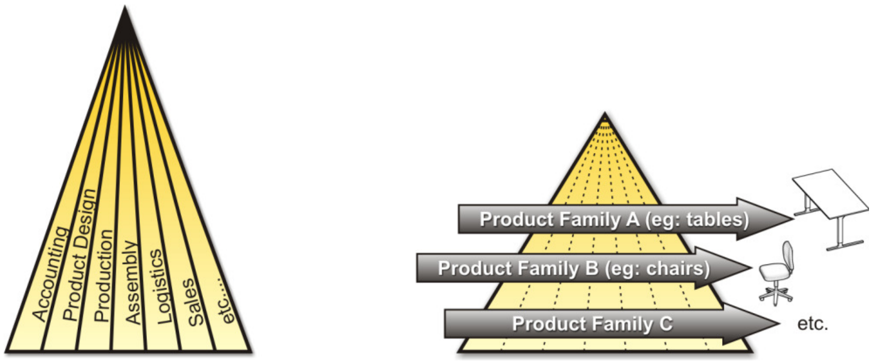

Figure 2: Department based high hierarchical organisation vs. a flatter product-oriented one.[27]

Other possible segmentation possibilities are also mentioned in the literature, for example a market-based segmentation,[28] whereby each segment focuses on one product-market combination, having a specific marketing strategy. For example, one focuses on quality-conscious buyers, while another on cost-optimisation for price-sensitive customers. In this way, none of the units is forced to make bad compromises.

[23] For more on *Voice of the Customer* (VoC), see: Wikipedia: Voice of the Customer, http://en.wikipedia.org/wiki/Voice_of_the_customer
[24] For more on *Quality Function Deployment* (QFD), see: Wikipedia: Quality function deployment, http://en.wikipedia.org/wiki/Quality_function_deployment and the QFD Designer at http://www.ideacore.com/
[25] See also: Weber, 2004, pp. 9-11. *(Note: „horizontal" and „vertical" is used in some sources the other way around.)*
[26] They can also be called *cost centers*, which however has a negative undertone, suggesting it "just eats up money", in contrary to a *profit center* which "makes a profit."
[27] Own drawing.
[28] Westkämper et al., 2001, pp. 76-77.

2.4.3 Defining Product Groups

The reason for product families is *"the aim of making mass customization a reality, offering a wider variety of products while at the same time reducing product cost by standardizing components and processes."*[29]

As the demands of the customers rise, while the marketplace becomes more and more globalised, **mass customization** has become an important key success factor. No company can afford to lose customers and therefore market share to its competitors because it could not meet the exact requirements of these clients. An increasing product variety, if not handled correctly, means increasing costs, more complex processes and ever more capital bound in mountains of inventory. A solution presents itself in the form of product families, whereby each family has a large number of parts that are the same, or are produced in the same way. In short: **standardisation** is used to drive costs down.

A widespread version of this is *modular design*, where some standard modules are mixed and matched to produce the different products. If there is one central module that is used for all products, it is called a *platform*, which is then expanded with different modules to produce the customised end products. This is called *platform design* and is used extensively, for example in the automobile industry.

As a start of a lean assembly line and material flow (re)planning, the product families should be created. There is no well-defined or prevalent methodology for this and in most instances this step can be carried out intuitively by a cross-functional team. Some of the factors to consider include:[30]

1. <u>Market considerations</u>: the aim is to satisfy customer expectations, the method of Quality Function Deployment (QFD) has been successfully used in this respect for a few decades. It is used to translate the needs of the customers into product features, and show the relevance and relative importance of these features. *Market segmentation* also plays an important role, whereby a segment is a group of (potential) customers with similar needs and patterns of behaviour. Product groups can be used to address each segment. The creation of segments is usually a task of marketing and product design.
2. <u>Product considerations</u>: during product design, thought must go into enabling product families by creating generic subassemblies and making mass customisation not only possible, but cheap. There are a number of ideas and methods for this in the literature.
3. <u>Product family considerations</u>: once the separate products have been designed, they need to be incorporated into groups, and variants need to be built according to the customer needs. An overview of the methods is given by Barajas and Agard.[31]

[29] Barajas, Agard, 2009, p. 2.
[30] Ibid., pp. 2-9.
[31] Ibid., pp. 6-9.

One simple approach is to make a table containing a list of all the products of the company as rows, and all the processes used in columns. Then mark all the cells where a specific process is used to manufacture a specific product. Finally group the products together that have the same or very similar *process profiles*, and so create the groups (see the table below for an example).

			Process				
Description	Product	Product Family	L101 Coils Bending		L101 Unit Brazing	L101 Unit Ass'y	L101 Unit Packing
			Machine	Labor	Labor	Labor	Labor
TWK 530 NBL	22227777-000	1			X	X	X
TWK 530 NBL-OC	22227777-CDT	1			X	X	X
TWK 536 NBL	33338888-000	2	X	X	X	X	X
TWK 536 NBL-OC	33338888-CDT	3		X	X	X	X
TWK 048 NBL	44447777-000	2	X	X	X	X	X
TWK 048 NBL-OC	44447777-CDT	2	X	X	X	X	X

Table 2: Process profiles of products, the colours indicate product families[32]

A larger company with many products and many varieties might require a more structured approach, Barajas and Agard give a seven step methodology for product family formation with fuzzy logic.[33]

2.5 Lean Phase 2: VALUE STREAM

In the general lean implementation method, after having defined the *value* – the products or product groups – and gathered the base data, the *value stream* needs to be defined. Then the current state can be mapped and analysed, to find all possibilities for improvement and redesign.

2.5.1 Selecting the Value Stream

A redesign of the whole assembly might overload the resources and tire the employees, before any major improvement can be realized. Many sources therefore recommend to focus on one product (or family) at once, plan the assembly and the attached material flow and then move on to the next one. This not only makes the project less resource-demanding, but enables a "quick-win", showing large improvements in assembly time and space requirements already early in the project.

[32] Source: Magnier, 2003, p. 5.
[33] Barajas, Agard, 2009, p. 9.

The first product family to focus on should be one with a lot of room for improvement and/or one that is important, for example because of high production volume. Tapping et al. give two methods to help select the first product to concentrate on:

PQ Analysis[34]
The Product Quantity Analysis is used to display the product mix as a Pareto-Chart (or ABC-chart), based on production quantity. The product quantities of the past three to six months are averaged, and the products are listed in decreasing output quantities per month. These are mapped as a bar chart, and on the same chart the cumulative quantities are mapped as a curve. This should make it obvious where a new assembly material flow would bring the most profit, i.e. the first products on the chart.

PR Analysis[35]
If there is no clear difference between "important" and "less important" products, the Product Routing Analysis helps. This is basically the same method that was used in *Section 2.4.3* to define product groups. The products are analysed according to their production/assembly process routes and the similar ones are grouped together. Then the PQ analysis can be used on the cumulative quantities of each group.

2.5.2 Value Stream Mapping

> *"A value stream map gives a visual representation of material and information flow for a product family (value stream), it is indispensable as a tool for visually managing process improvements."*[36]

Value Stream Mapping is a tool that will be used during planning in *Chapter 5*, as an analysis of the current state of production/assembly. There are actually several analysis methods in the literature, but VSM seems the most adequate general analysis tool for the following reasons:

- It belongs to the lean toolbox and has a very prominent place there, as many sources include the application of VSM as an integral part of a lean transformation.[37]
- The method has a broad range, going through all the steps of the value stream from the suppliers to the customers, giving a "big picture" overview of the company.
- The graphic representation and the fact that the whole map fits on one page enables a quick and thorough summary.
- What it gains in overview, it loses in detail: for detailed planning, specific tools must be used to complement VSM.

[34] Tapping et al., 2002, p. 28.
[35] Ibid., p. 30.
[36] Ibid., p. 78.
[37] See for example the publications of the Lean Enterprise Institute, http://www.lean.org

In the following, the basic approach of VSM will be presented, based on the book *Value Stream Management*.[38] It is useful to first overview the symbols used, mostly the same across publications:

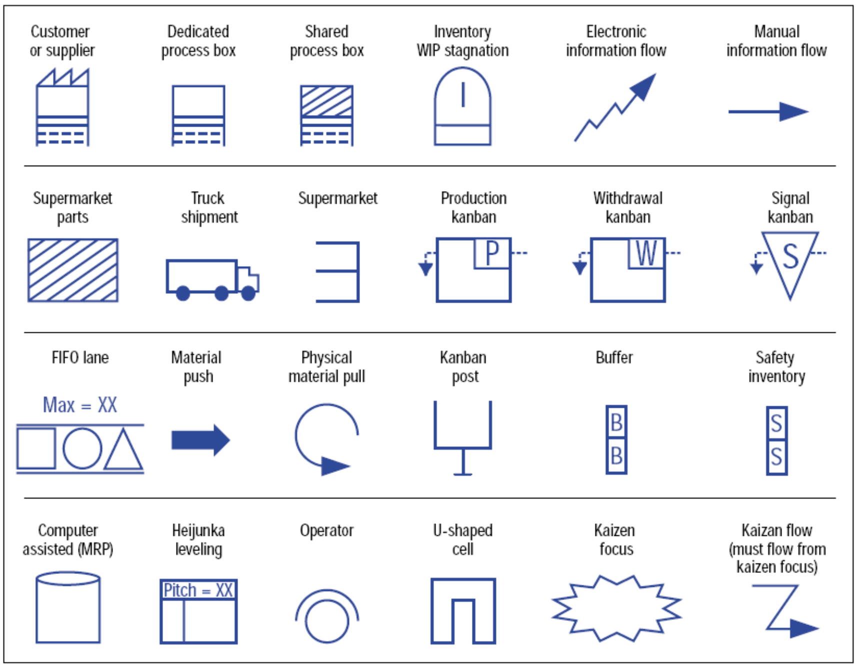

Figure 3: Value Stream Mapping Icons.[39]

Preparation

Step 1: In the team, the operations are thought through and a rough sketch is made, this is the preparation. Gather the main points to look for and the main data to collect in a checklist.

Step 2: Go to the shop floor and gather data. This is an important distinctive feature of lean over traditional methods: one must go to the "actual thing" – *gemba* in Japanese – that is the shop floor and observe it, instead of sitting in the office and using theoretical data. Using the checklist, go through the value stream starting from downstream (i.e.: shipping) and stepping upstream till purchase. Not only data, but any remarks and observations should be noted to ease the planning phase.

> *Note*: be sure to observe the proper etiquette of shop floor research, including informing the workers about what is going on and why and openly answering their questions.[40]

[38] Tapping et al., 2002. Note that Value Stream Mapping has a very unified structure including the symbols used, so that other publications on the subject mostly contain a very similar approach.
[39] Source: CD insert in Tapping et al., 2002.
[40] Tapping et al., 2002, p. 81.

The important parts of the checklist, in a few logical groups:

VSM Information Gathering Checklist

Times
- □ Total time per shift
- □ Planned downtime
- □ Planned maintenance schedules
- □ Available time = Total time – planned downtime

Shipping data
- □ Schedules and quantities
- □ Parts per container
- □ Quality of shipped parts

Process data (gather for each process)
- □ Cycle time
- □ Changeover time
- □ Work-in-process (WIP) amounts (before the process)
- □ Lot sizes / economic lot sizes
- □ Number of operators
- □ Uptime

Other data and observations
- □ Disruptions to flow
- □ Exceptions due to rework
- □ ____________________________
- □ ____________________________

Examples

Times
- □ 8,5 hours per shift
- □ 30 minutes (unpaid lunch break) and 2x10 minute breaks
- □ None
- □ $8{,}5 \cdot 60\, min\ - 30 - 2 \cdot 10 =$ $460 \text{ min} = 27600 \text{ seconds}$

Shipping data
- □ 504 units per day (average)
- □ 12 per container, 42 containers per day
- □ 99,6 %

Process data (e.g.: machining)
- □ 42 seconds
- □ 45 minutes
- □ 2450 parts before machining
- □ 20
- □ 1
- □ 99%

Other data and observations
- □ ________________
- □ ________________
- □ ________________
- □ ________________

Step 3: the data gathering is discussed in the team and double checked so that nothing is missing.

Drawing the Map

The actual map is drawn, using the symbols above, not forgetting that one plan is for one product or product family only. There is no prescribed way to do it, the approach in the aforementioned publication is described here shortly (underlined words represent what needs to be drawn):

1. Draw the supplier icon in the upper left and the customer icon in the upper right corner of the page, and the production control icon in between them.
2. Draw a data box under the customer and enter the customer requirements in units/month, units/day and containers/day. The units/day is equal to the units per month divided by the number of shipping days, e.g.: 21 days.

3. Draw a truck icon with an arrow under the suppliers and enter the supply frequency, for example weekly. Do the same for the customers, enter the shipment frequency, e.g.: daily.
4. Draw the production and assembly operations from left to right along the bottom, leaving space between each. Each one should be a small box with the name of the operation at the top.
5. The process data that was collected earlier is now entered under each process box:
    - Number of operators
    - Cycle time in seconds
    - Changeover time per shift in minutes
    - Available production time in seconds, using the example above: 27600 s
    - Uptime in %, using above example:

$$uptime = \frac{available\ time - changeover\ time}{available\ time} = \frac{27600 - 45 \cdot 60}{27600} = 90{,}22\%$$

6. The information flow is drawn:
    - Arrows from customers to production control for the forecasts and the orders, with the frequency of these.
    - Draw communication arrows from production control to the suppliers, once again giving the frequency of forecasts and orders.
    - Draw the production supervisor in the middle. Using arrows with text, indicate the frequency of order release from production control to the supervisor. Then draw arrows from supervisor to the processes that are scheduled, giving order release frequency.
7. Draw triangular inventory icons between all processes where inventory exists and write in the average number of WIP units.
8. Draw a horizontal timeline under the processes, this is usually drawn in a step-form, so that the lower "steps" are under the value-adding processes and the higher steps are between the processes where no value is added.
    - Now the times are added to the timeline. In the lower steps under the processes write the cycle time and between the processes write the days on hand of the current WIP, where:

$$WIP\ days\ on\ hand\ (DoH) = \frac{number\ of\ WIP\ units}{number\ of\ units\ shipped\ per\ day}$$

9. Finally, draw the material flow between all processes and inventories, using the proper icons depending on the material flow type:
    - If a process produces to schedule, irrespective of the following process, it is push.
    - Other scenarios are combinations of pull, supermarket, FIFO (first-in-first-out), these are however usually not present in non-lean factories.

10. As a summary, the total cycle time and the lead time are calculated.

Summing up CT_k = cycle time of process k:

$$Total\ Cycle\ Time = TCT = \sum_{k=1}^{n} CT_k$$

Summing up WIP Days on Hand before process k:

$$Lead\ Time = LT = \sum_{k=1}^{n} WIP\ DoH_k$$

To wrap up, make sure everyone agrees on the map and post it on a board for everyone to see, adding the date to it.

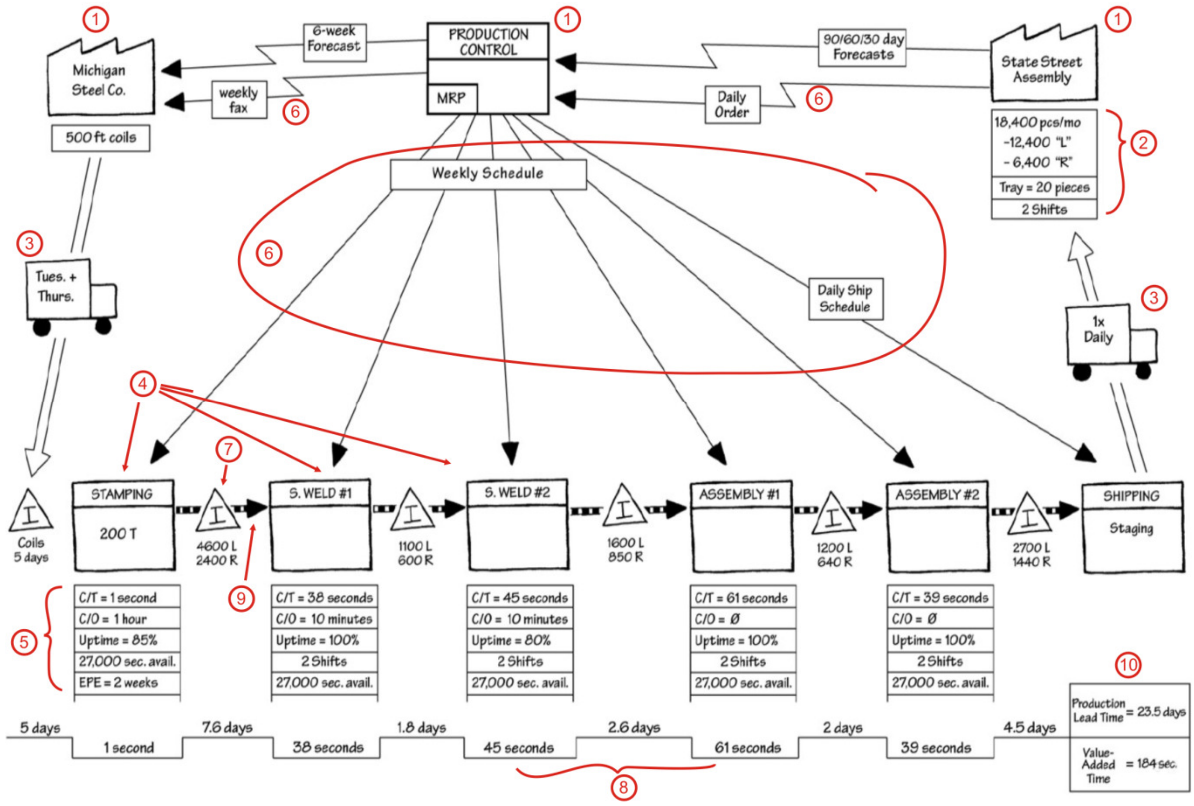

Figure 4: Example value stream map showing steps of construction.[41]

[41] Source (with added step numbers): Womack, 2009, p. 35.

Usefulness and Limitations of VSM

The “value” of a value stream map is indisputable, it has been used first at Toyota and after gaining exposure in the Western press also in America and Europe successfully. It is however not without its shortcomings, these should be taken into consideration. One such detail is that while a good map shows information and material flows and can show the wastes in these, there are other wastes in production/assembly that are not mapped, for example the area used, the excess lighting and heating as a result of this, as well as human factors, such as workers not used according to their abilities or potential.

Another consideration is that during information gathering on the shop floor a number of observations are made that aren’t needed for the map. These can however contain vital information for planning, therefore a tunnel-vision concentration on just the map is unproductive. One must also bear in mind that this is just an overview and the details are just as important.

2.5.3 Value-adding Operations

One of the central pillars of lean manufacturing is the continuous elimination of waste – *muda* in Japanese[42] – that is, all steps that absorb resources but do not create customer value. The literature differentiates three types of operations:[43]

1. Value-adding operations: these are necessary for the product and increase its (customer-perceived!) value, the objective here is to shorten the length of these operations and save on costs.
2. Non value-adding (*“NVA”*) but necessary operations (type one muda): the objective is to eliminate these steps in the long run through redesign of the assembly process.
3. Non value-adding and unnecessary operations (type two muda): these can be eliminated in the short run.

The steps of the production and assembly value stream need to be categorised into one of these types, and the objectives for each of the three types need to be considered during planning.

The ratio of total cycle time to lead time shows us in what ratio of time value is added to the product, with the assumption that all processes where the product is worked on are value-

[42] Note that waste in a broader sense is divided by authors into three types: *muda* (non value-adding steps, waste in the narrower sense), *mura* (performing tasks inconsistently, in a Six Sigma sense having a large process variation) and *muri* (excessive stress & strain required to perform a task, the lean objective being to enable every worker irrespective of physical characteristics to do all tasks). See: The Northwest Lean Networks: Lean Terms and Definitions, 2009.

[43] Womack, Jones, 2003, p. 38.

adding. In a traditional non-lean company, the lead time can be upwards of several weeks, while the cycle time is not more than a few minutes. Womack and Jones give an example, a can of Cola, with a lead time of 316 days compared to about 10 minutes of valuable cycle time (half of which is the drinking of the cola by the end user!).[44] During most of the time the product is waiting for the next operation, being moved between two operations, waiting for shipment or being shipped. Results are all the disadvantages of long lead times, including bound capital, decreased flexibility to changes in the market or in customer habits, late discovery of quality problems and the list goes on.

2.5.4 Types of Wastes

The literature differentiates among the following types of waste. The first seven were introduced by Taichii Ohno,[45] the last one is from Womack and Jones.[46] The ones related to material flow are highlighted in bold.

1. Overproduction: production of goods not needed, typical example being make-to-stock.
2. **Movement of Material**: unnecessary transport of material. The ideal would be a material "flow" with no movement at all; since this is impossible, the transport needs to be minimized, e.g. with a better layout.
3. Motion: excess motion of employees, such as searching for tools.
4. **Waiting**: unused time of employees waiting for a machine to finish or for the previous process to deliver parts, etc. This time could be used productively.
5. **Inventory**: too much stock, which can have three forms: raw materials, works in progress and finished goods.
6. Unnecessary Processing: unneeded processing steps, this one is harder to find and eliminate.
7. Defects and Correction: the wasted time to rework parts and products that were not made correctly the first time.
8. Bad design: design of products and services that the users don't need.

Tapping et al. divide the wastes into three types according to how easy they are to spot and eliminate:[47]

- Level one or gross waste can be found and removed easily, such "low hanging fruit" can be a good place to start, examples being bad layout, rework, wrong batch size, etc.
- The second level involves waste within the process or the method, such as problem with equipment or workplace layout.

[44] Ibid., p. 43.
[45] See: Taiichi Ohno: The Toyota production System: Beyond Large Scale Production, Productivity Press, Portland 1988.
[46] Womack, Jones, 2003, p. 355.
[47] Tapping et al., 2002, p. 42.

- Finally, the third level contains the microwaste within processes, like having to walk too long or excess paperwork, which can only be removed once the larger wastes are gone.

2.5.5 Takt Time

A really important concept in lean and other modern production systems is the *takt time*, derived from the German word for beat or rhythm. This is a determining factor for both the assembly line and its material flow. The takt time is not an attribute of any manufacturing process and it cannot be measured – according to Miller a common misconception[48] – it is a function of the demand as follows:

$$takt\ time = \frac{available\ operating\ time}{production\ requirement\ (= demand)} = [time/piece]$$

The takt time expresses in "seconds per piece" the speed of sales. It is important here to look ahead at the anticipated future demand in the calculation. This is the ideal or target cycle time or *work pace*, calculated for each product, from which any deviation lessens the effectiveness of the factory. If the cycle time is longer than takt, then the company very simply cannot meet the customer demand, leading to increasing delivery times and lost sales. Although speeding up production faster than takt might seem like a good idea at first, however, it results in the wastes of overproduction and excess inventory.

One example where the work pace can be sped up faster than takt is to compensate for rounding "errors" in the number of operators.[49] In a one-piece flow assembly line the number of operators are calculated as following:

$$\#\ of\ operators = \frac{manual\ cycle\ time}{takt\ time}$$

That is, a cycle time twice as high as the takt time needs two operators on the line. Since this division is very rarely a round number and there are no "0,71 persons", it must be rounded. If the number is rounded up, there are more people than needed, the work pace is higher than takt. They reach the daily demand faster and when done, can be rotated to another job or for example process improvement activities. The real "lean way" is however to round down the number of operators and then reduce the cycle time through process improvement activities (*kaizen*) to make up for it.

[48] Miller, 2004.
[49] Ibid., for a calulation example, see there.

50 second rule

A note should be made here about a rule of thumb called the 50 second rule,[50] which says that cycle times should never drop below about 50 seconds. If the takt calculates to 30 seconds, two assembly lines are needed, each at 60 second takt. Reasons for this are manifold, for one the productivity is higher, as lost times make up a higher percentage of time in a fast 30 second line than a slower, e.g. 60 second one. For example, 3 seconds lost in an operation due to wasteful movements, searching, etc. make up a 10% loss in the faster line, but only 5% in the slower one, and even less if the line has an even higher takt. Second of all, safety and ergonomics dictates that the same motion should not be carried out too repetitively: in the slower line the muscles have a full minute to relax before coming to the same motion again, while only 30 seconds in the faster one. The quality is also increased, since in the slower line the operators have more tasks to do which means for several tasks they will become their own "customers". In this way they see their own mistakes and do not just pass them to the next one on the line. Finally the morale is improved as the job becomes less monotone:

> *"People enjoy the cross training and learning new skills, the reduction of repetitive motion fatigue, but the top reasons is that people like to feel that they are building something rather than just running a bolt and putting a plug a hole all day long."*[51]

2.5.6 Pitch

The pitch serves to divide the production time into chunks larger than the takt time; these are the increments in which production is scheduled. If more products are assembled on one line, as is very often case, then production levelling occurs in multiples of pitch, see *heijunka* in *Section 2.7.6*. It can be convenient to determine the pitch based on shipping container size:

> *"The pitch is the amount of time – based on takt – required for an upstream operation to release a predetermined pack-out quantity of WIP to a downstream operation."*[52]

$$pitch = takt\ time \cdot pack\ out\ quantity = [s]$$

For example, the products are shipped 12 to a container while takt time is 65 seconds. Then: $pitch\ = 65\text{s} \cdot 12 = 780\text{s} = 13\text{min}$, meaning that every 13 minutes a container must be filled and sent to shipping.

[50] Ibid.
[51] Ibid.
[52] Tapping et al., 2002, p. 111.

2.5.7 Capacity

The capacity shows how well the company can meet customer demand.

$$Capacity = \frac{Available\ production\ time}{Current\ cycle\ time} \cdot Uptime[\%] = [pieces]$$

If the capacity of the operations all lie above the required daily amount then the company is theoretically able to meet demand. If in spite of this the on-time delivery rate lies significantly below 100% then it is *not* meeting demand, there are other problems and waste in the system that need to be found and eliminated. If the capacity lies under the demand, then the given processes or operations need to be revised, improved or replanned.

2.5.8 Bottlenecks and Constraints

The process with the smallest capacity (i.e.: with the longest cycle time) is the "bottleneck", since it reduces the output of the system, irrespective of the speed of the other operations. The objective here is to feed the bottleneck constantly with material, since any unused time on the bottleneck reduces the system output. This can be done with for example some buffer stock before the bottleneck. Process improvements can eliminate the given bottleneck, but then another process becomes it, i.e.: every system has a bottleneck. The real question is whether the bottleneck can meet customer demand, if yes, then it is less a problem.

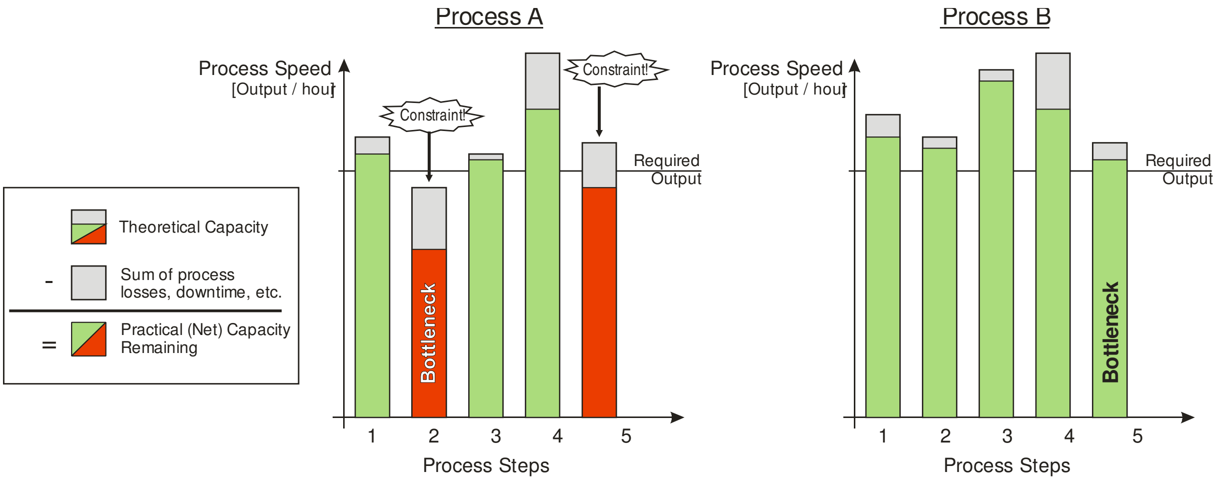

Figure 5: Constraints and bottlenecks.
While both processes have a bottleneck, only Process A has constraints that prevent meeting demand.[53]

If the capacity of a process lies under the demand, or in other words, its cycle time lies over the takt time, it classifies as a "constraint." This cycle time includes downtimes, inefficiencies and such. These constraints must be removed to meet demand. The figure above shows two

[53] Own diagram.

example processes with five steps each and their capacities in output/hour. The grey areas are the downtimes, losses, inefficiencies and changeovers that must be subtracted. Red indicates net capacities below demand, even if the theoretical capacity is over demand, such as the fifth step of Process A.

2.5.9 Stock at Shipping[54]

Buffer Inventory
Even if the capacity of the line is just correct, the customer demand is a stochastic process, and while the takt time is its average value, it deviates from this. The buffer is an inventory of finished goods available to the customers to counterbalance the fluctuations in demand.

Safety Inventory
In a similar way, the internal production/assembly processes might have disruptions and inefficiencies. The safety inventory disconnects the customers from these variations, more process variation mean more safety stock is needed. Tools such as six sigma can lower the variability of processes and reduce the need for such a solution.

Finished-goods Supermarket
Finally, a store of finished-goods at shipping may be necessary if the production processes cannot guarantee a continuous flow of products or if the lead time is longer than the time customers are willing to wait. In this "supermarket" a set level of each product is stored, which are then replenished as they are "pulled" by the customers. This inventory level is independent from any existing buffer or safety inventories.

2.6 Lean Phase 3: FLOW

A central idea in lean is the ***flow of value***. The analogy of a value "*stream*" is carried on, this stream needs to "*flow*" without barriers or constraints, meaning that value – that is, products – can move quickly from suppliers to customers.

The idea of flow is exactly contrary not only to traditional mass manufacturing but to what we have been accustomed to through the years. Womack and Jones sum it up well:

> *"We are all born into a mental world of 'functions' and 'departments,' a commonsense conviction that activities ought to be grouped by type so they can be performed more efficiently and managed more easily. In addition to getting tasks done efficiently within departments, it seems like further common sense to perform like activities in batches."*[55]

[54] Tapping et al., 2002, pp. 113-116.
[55] Womack & Jones, 2003, p. 21.

The meaning of batch-and-queue and its negative effects have already been discussed in *Section 2.1*. During the reengineering movement some of the problems were addressed and the focus was shifted from functional departments to value-creating processes. Process management didn't go as far as lean, it still deals with aggregate processes (eg. order-taking) for all products, instead of focusing on the value-creating activities for one specific product. Besides this, the reengineers had treated employees as enemies, many lost their jobs and the ones surviving a "company reengineering" were demoralised.[56]

The objective of lean here is to **concentrate on the product** being produced and follow it through a row of value-adding steps to completion. The work of employees are redefined to make a positive contribution to value-adding and make them interested in creating value. This is the real goal of a lean enterprise.

Depending on the level of flow realised, there are about five flow possibilities in production or assembly lines. Below, the solutions are presented to understand how they work, what benefits they bring and what they require. These build the basis of *Phase 4* in *Chapter 5*.

2.6.1 Continuous Flow / Single Piece Flow

Continuous flow (also known as single piece flow or one piece flow[57]) is a special production or assembly line organisation that is described by most sources to be the ideal manufacturing system and has the following characteristics:

- At each step of assembly exactly one part is worked on, when finished it is passed to the next station and a new part is pulled from the previous station. It is therefore also called "make one, move one." This means the batch size is equal to one.
- The scheduling point – i.e. the process where the orders are given – called the *pacemaker* in lean, is upstream relative to the continuous flow line. The selection criteria for the pacemaker will be discussed later.
- There is no inventory (WIP) in the process except the parts that are being assembled. This leads to the maximum possible reduction of inventory in assembly.

This system was already used by Ford in his plant, where the cars were attached to a strong rope and were pulled from workstation to workstation at regular intervals.[58] At each station one operation was done on the product, so that operation time was less than takt time. The workers either stood at their own stations or travelled along with the product, these being the

[56] Ibid., p. 24.
[57] **A note on terminology**: while *"one piece flow"* in the English literature – though rarely used – is a synonym of *"single piece flow"* = *"continuous flow"*, in the German literature it is used for a type of job assignment to operators in a flow cell, also called *"circulation"* or "*chaku-chaku"*, see Section 2.6.7. In order to avoid confusion, this paper will avoid the term one piece flow and use *single piece flow* for the type of flow, and *circulation* for the work arrangement.
[58] Arzet, 2005, p. 7.

two fundamental work forms in a continuous flow line even today: the former is the *conveyor-belt system*, the latter is *circulation* (*"chaku-chaku"* in Japanese).

Benefits

There are a large number of benefits through implementing continuous flow, the following are given by MacAdam:[59]

- *Improved Productivity*: through elimination of the wastes of excess motion, transport and waiting. Parts do not need to be picked up and put down many times.
- *Shorter Lead Times*: there is no inventory between steps, therefore huge reductions in lead time, upwards of 90%. Now:

$$lead\ time_{single\ piece\ flow} = number\ of\ stations \cdot cycle\ time$$

- *Improved Quality*: Large inventory between steps means hundreds of products are made before discovering an error, this is greatly reduced.
- *Reduced Floor Space*: through elimination of storage space and transportation, the products can go from hand to hand, taking of course the physical size into consideration.
- *Better Response to the Customer*: Without large WIP inventory, changing customer demand can be closely followed and new products can go through the system quickly.
- *Improved Management of the Process*: MacAdam here refers to a good visual control of the status of orders.
- *Cleaner Work Environment*: The principles of 5S are implemented in the new work cell.
- *Improved Teamwork and Better Communication*: due to the proximity of the value-adding steps to the operators.

Requirements

To be able to sustain a continuous flow through the value stream, some requirements need to be met:[60]

- All operations < takt time. This is a very basic requirement for any assembly line. If this is not met, then more parallel lines are needed for the same product family.
- A so-called *basic stability* is needed, which according to Dolcemascolo entails the following:
  - Highly capable processes: "Processes must be able to consistently produce good product. If there are many quality issues, one-piece flow is impossible."
  - Highly repeatable processes: "Process times must be repeatable as well. If there is much variation, one-piece flow is impossible."

[59] MacAdam, n.Y., p. 2.
[60] Dolcemascolo, 2007.

- Equipment with very high (~100%) uptime: "Equipment must always be available to run. If equipment within a manufacturing cell is plagued with downtime, one-piece flow will be impossible."[61]
- Given this basic stability, continuous flow can be achieved. Tools for achieving stability are, among others, TPM (Total Productive Maintenance / Management), 5S (Sort, Set-in-Order, Shine, Standardize and Sustain) and statistical tools such as Six Sigma (for reducing process variation).

- For *one piece* flow a batch size of ONE for all steps should be possible. This means:

$$\text{operation time} + \text{changeover time} + \text{transport time} < takt\ time$$

AND

$$\text{processing of one piece at a time possible}$$

that is, it should be possible at each step to make a different variant, including making any changeovers that are needed. If either one of these is not possible, then a batch size greater than one needs to be used. Typical examples of steps that do not meet this requirement are large machines, paint booths, wash booths. In case of these operations there are a few solutions to still be able to use continuous flow:

- Scale the machine down so that one piece fits and reduce changeover times.
- Move the variety adding step *after* the problematic operation, in this way eliminating changeovers at this step. This naturally needs to be compatible with the product structure.
- Change the process or the product in such a way as to evade the problem.
- Continuous flow can also function with small batches, so that the *production unit of measure* is redefined from 1 piece to this batch size. This means however that this unit needs to be used in other areas and calculations, such as calculating the takt time.[62]

An alternative is a solution where continuous flow is partly maintained:

- Disconnect the operation so that the rest of the value stream can still produce in continuous flow. A batch needs to be built before the problematic operation.

- All process steps should be scalable to takt time, be that downscaling or upscaling. If takt time is 15 minutes, then the machine needs to be able to output one workpiece every 15 minutes.

[61] Dolcemascolo, 2007.
[62] See the Glossary of Terms for Lean Process Improvement, http://systems2win.com/c/time_definitions.htm (accessed on: 27.08.2009).

2.6.2 Flow (FIFO Flow)

If the requirements of *continuous flow* cannot be met, the next best solution to consider is a *flow* system. This has the basic properties of continuous flow: the orders are sent to one station in the process, this is the pacemaker. No other communication is needed to the other stations. The products flow through the processes on a First-In-First-Out basis. There is in process (WIP) inventory between each operation, these are however limited. The works in progress serve as buffers to help balance the assembly line against fluctuations. They also enable small batch sizes of over 1, if a particular task cannot be downsized to one piece flow.

The assembly line is a pure flow system if the first operation in the process is scheduled, that is, the pacemaker is at the beginning. From there the products flow till the last operation, and one product comes off the line in every takt time interval. Production control does not need to send work orders to any of the downstream workstations. The result is a smooth continuous flow of value with little waste, this is the ideal state. This level of flow requires "*FIFO lanes*" preceding each operation or just preceding particular operations, this must be determined during planning in the project team.

Requirements
The requirements for flow are manifold,[63] these also apply for single piece flow:

- Process and worker capability: the work team needs to be cross-trained in every task, so that they can be deployed flexibly, for example if someone is ill. The machines need to be up and running 100%, this can be accomplished with the tools of TPM. Both people and machines need to work accurately and without errors.
- The work must be standardized, by the work team itself! Rother points out[64] that a common pitfall is using calculated standard times instead of going to the shop floor and measuring them in reality.
- Poka Yoke, visual controls, 5S and other techniques from the lean toolkit will probably be needed to enable flow.

2.6.3 Part Pull, Part Flow

If there are obstacles to having a full flow system, the next best solution is having parts of the line function with small inventories, with a pull system such as kanban between steps. Such an obstacle can be for example tasks, especially when machines are involved, that cannot operate on one or just a few products at once. These have to operate in batch mode, thereby breaking the flow. Let's say an example company manufactures some plastic components for its products itself using injection moulding. This machine could not produce just one piece economically, but maybe one hundred, breaking the flow.

[63] Womack & Jones, 2003, pp. 60-61.
[64] Rother, n.Y., p. 2.

Such a case means that not all tasks can be connected with simple FIFO flow. Everything after the pacemaker *flows*, while every operation preceding it is *pulled*. In our example, the pacemaker can be the operation right after the injection moulding. All assembly operations following it can use FIFO flow. The pacemaker itself pulls material from the injection moulding machine, and that in turn pulls material from any operations that might precede it.

2.6.4 Choosing the Pacemaker

The pacemaker operation – also called the *scheduling point* – is the one receiving the orders. The selection of the pacemaker process is a very important decision. It affects the rest of the value stream. Please observe the following requirements:[65]

- No downtime
- No changeover or very little (max. 1 minute)
- Greatest worker flexibility

The part of the value stream that meets these requirements is often the (final) assembly.

Since the ideal state is full flow, the pacemaker should come as early in the value stream as possible, while still meeting its requirements.

Some authors have compared the lean pacemaker process with the bottleneck in the *Theory of Constraints* (*TOC*, see the literature[66]). However, while in TOC the bottleneck sets the pace, in a lean system, the pacemaker is chosen independent of which process the bottleneck is. As Shook points out:

> *"Secondly, there is a fundamental difference between TOC "bottlenecks" and TPS "pacemakers," though they are frequently misunderstood to be roughly analogous. What is analogous is that TPS, like TOC, strives to identify and "break" bottlenecks. But, TPS does not allow a bottleneck to set the pace of the value stream. After all, the bottleneck may exist for any number of problematic reasons – excessive downtime, poor quality, long changeover times, etc. Why would I choose to let an operation with such problems determine the way I flow my entire value stream? Of course, I have to deal with the problem operation (the bottleneck), and there are numerous techniques to do so, but I will not let it dictate the pace (takt) of my entire product flow!"*[67]

[65] Tapping et al., 2002, p. 66.
[66] For a good TOC summary, see: Wikipedia: Theory of Constraints, http://en.wikipedia.org/wiki/Theory_of_Constraints
[67] Shook, nY, http://www.lean.org/Library/Shook_on_VSM_Misunderstandings.pdf

2.6.5 Full Pull

It can still happen that there are obstacles to the part pull, part flow solution, for example a large batch machine at the end of assembly, which prohibits any FIFO flow even at the end of the line. In this case a full pull system needs to be designed. Finished products are shipped from a finished-goods supermarket, the supermarket is replenished by the last assembly operation which is the scheduling point, while this pulls on all of the previous operations, right up till the raw material warehouse. This system is also lean, as exactly what the customer needs, when he needs it is produced, just-in-time. There is however inherent waste, such as inventory between each step and a longer lead time compared to single piece flow.

The techniques for pull in lean are either *supermarket* or various forms of *kanban*, which will be discussed in detail later, while other solutions also exist such as *production authorization cards* (PAC) and others.

2.6.6 Work Cells

Work Cell Basics

> *"For most companies, workcells are the heart of their Lean Manufacturing strategy (or should be). Workcells untangle complex material flows, promote teamwork, reduce queuing and improve the process in many and varied ways."*[68]

In contrast to traditional production with machines grouped according to their functions, the modern approach is product- or product family- and therefore in the end customer-based. A cell is

> *"An independent business unit, complete with all the required resources to produce a product or to provide a service. Most commonly referred to as 'production cells', 'manufacturing cells', or 'service cells'."*[69]

That means that for each product or product family a manufacturing unit is created, which has all the necessary resources for carrying out the production or assembly. In our example of a mainly manual assembly of an average-sized product, this would be the complete assembly from parts to final product. In case of larger, more complex products more cells would be needed along the value stream, for example preproduction, production, sub-assembly and final assembly.

[68] Lee, 2003.
[69] The Northwest Lean Networks: Lean Terms and Definitions, 2009.

Benefits

Work cells are much older than Lean, Toyota or Ford for that matter. They were a good solution in small manufactures, where production volume was low and variety high. A work cell makes it possible to make every product exactly to customer needs. The mass production revolution brought a high specialisation of tools and a one-sided focus on economies of scale. The machines became ever faster, so fast that additional products had to be processed on one machine, this led to the necessity of changeovers. Due to long changeover times on the large machines, the machines had to produce in large batches, leading to high inventory, queues, waiting and a lot of waste and this kept on reinforcing the system in a circle.[70] Other problematic feedback loops also exist in push-based systems. Since one machine had to work on different products while the products had different processes and routes, no product-based sequential layout was possible, instead, the machines and tools were grouped according to function. The parts had to travel all over the shop floor, leading to more waste, more space needed and a chaotic material flow. Results were high inventory, little flexibility, long lead times and mediocre quality, all of them exactly opposite the goals we have set in chapter 3.

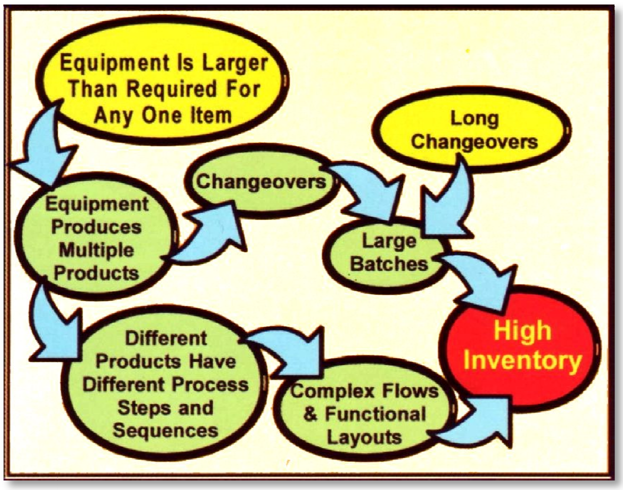

Figure 6: Some of the reasons for high inventory, simplified.[71]

To reach these goals cellular manufacturing provides a good solution, returning to the roots of manufacturing but equipped for today's needs. The intention of the developers of the Toyota Production System (Lean) was not the creation of a broad manufacturing system and management paradigm, but simply to solve these exact problems in their own company.

> *"Shingo attacked both root causes. First, he developed the SMED system that reduced changeover times and, thus, batch size and, hence, inventory. Second, he scaled down the equipment, where possible, thus enabling cellular manufacturing and its simplified workflow."*[72]

[70] Lee, 2007, p. 15.
[71] Source: Ibid., p. 15.
[72] Ibid., p. 15.

General Method

Lee gives a general method with four major tasks for constructing work cells, which are summed up in the following.[73]

1. **Selecting the products**. This is one of the first questions to clear in assembly and material flow (re)design and should already be done. For fewer products a few meetings and intuitive grouping is all that's needed. In case of complex portfolios with hundreds or thousands of products all with different processes and sequences, more advanced methods are needed, such as Production Flow Analysis[74] or the fuzzy logic method of Barajas and Agard[75]. The goal is to have a list of products and/or product families that will have their own work cell.

2. **Engineer the process**. Beginning with a Value Stream Map and, if needed, a detailed process analysis, the assembly process is simplified, streamlined and adapted to the cell. The operation times for each step in the process are needed to calculate the number of operators (= manual cycle time through cell / takt time), number of workstations and lot sizes.

3. **Design The Infrastructure**: Lee here refers to the immaterial infrastructure of the work cell, including *"scheduling methods, material handling, supervision, motivation, work balance, training and work assignments."*[76] There are many techniques and methods available here, one must investigate the literature and see which one works best in the given situation. One important aspect here is line balancing and how the tasks are divided between the operators, this will be discussed in the next subsection.

4. **Plan The Layout**: a prerequisite for this step is the proper completion of the first three tasks. Here all the physical elements, workplaces, tools, machines are laid out on a floor plan. While traditional cell shapes, such as the U, O or teardrop shape are suited for simpler, sequential material flows, the cell can also take on more complex shapes if the material flow so requires it, see *Figure 7* for an example. For the micro-design of the workplaces, see Nelson and Lee.[77]

[73] Lee, 2003.
[74] For Production Flow Analysis, see for example: Burbidge, John L.: Production Flow Analysis for Planning Group Technology, Oxford University Press, 1989.
[75] Barajas, Agard, 2009, p. 9.
[76] Lee, 2003.
[77] Nelson, Lee, 2003.

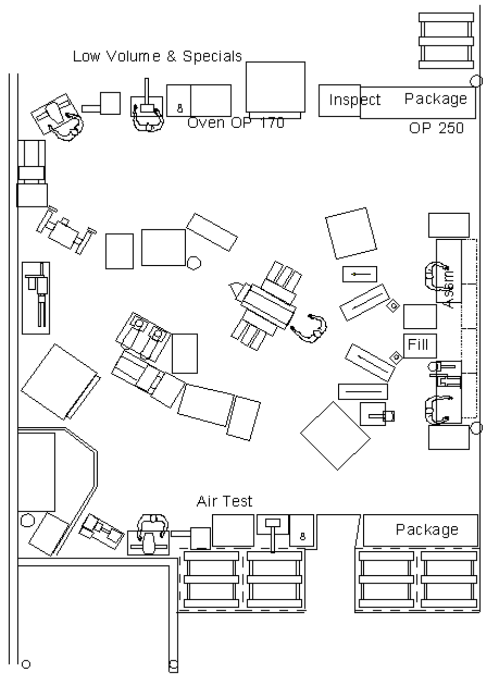

Figure 7: Example cell for more complex material flows.[78]

2.6.7 Line Balancing and Work Organisation in Cells

Along with cell planning the work of its operators needs to be planned. This step is also called line balancing: the operations can have different cycle times, while to eliminate waste and produce to customer requirements the cycle times need to be as close to the takt time as possible. They need to be "levelled", which is better seen on *Figure 8*.

Tapping et al. give a short method for line balancing. Basically the cycle times of the work elements and their assignment to the operators are determined. These are drawn for the current state on an *operator balance chart*, as in *Figure 8*. The number of operators (= available time / takt time) is calculated. Rounding their number up functions in the short term, but the goal is to be able to round down and still be able to meet the takt time by eliminating waste. How to reduce waste and how to assign the work to the operators is a creative process to be done by the project team. Then, the job assignment needs to be worked out.

[78] Source: Lee, 2003.

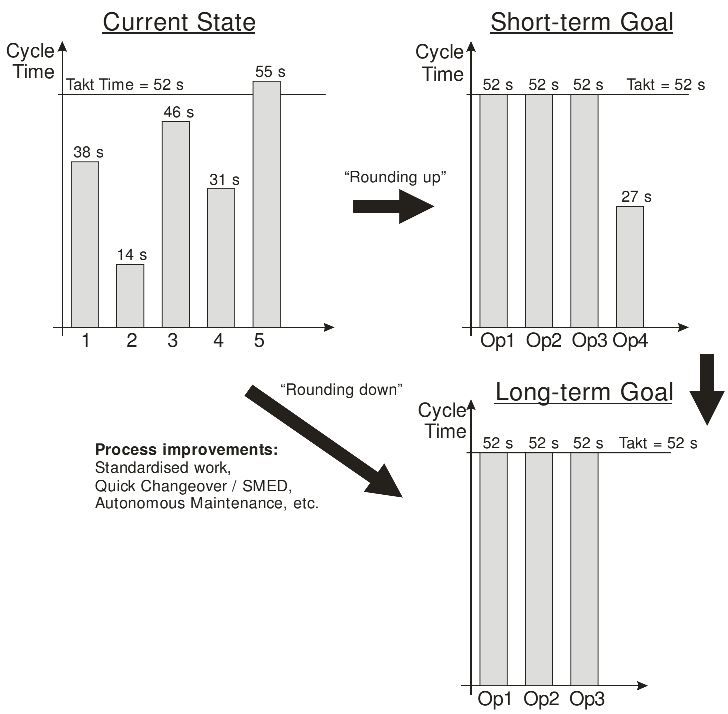

Figure 8: Operator balance chart, before and after.[79]

Best-case: Circulation

Many sources cite *circulation* (also called *caravan, rabbit-chase*[80] or *chaku-chaku*) as the best solution in a majority of the cases. The basic idea is that the operators in the work cells start at workstation one with one product, complete the task at the first station, walk to the next station with the product, do task 2, and so on, wandering through the cell without putting the product down, until this one product is finished. Then they start with the next product.

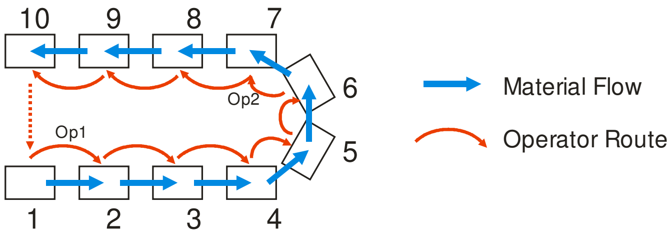

Figure 9: Circulation-type work assignment.[81]

There are a whole number of benefits from this solution, especially a high level of flexibility in many areas:[82]

- Fluctuations in production ±20% without productivity losses.
- No changeovers are needed for a new variant. A changeover in an assembly line that has no large machines to change over is made up of the time the operators need to read

[79] Own diagram, based on: Tapping et al., 2002, pp. 59-60.
[80] Baudin, 2003.
[81] Source (modified): Baudin, 2003.
[82] Arzet, 2005, p. 11.

and understand the work instructions for the new variant. Since only one operator receives the work order for that specific product, this only needs to be done once. From then on the person can build the given product without delays.

- It enables a batch size of one, in fact it requires it.
- A dynamic product mix is possible without loss in productivity, indeed, each and every one product can be different. This also leads to trouble-free changes in the variants or whole model changes, only the new work orders need to be printed.
- Flexibility concerning capacity: a work cell with *n* workstations can have between 1 and theoretically *n* operators (though not more than a few are recommended), operators can be added or subtracted as needed to balance the production to demand.
- A completely just-in-time production with minimal inventory is possible.
- It leads to a higher motivation of the workforce. For one they need to learn and do different tasks, instead of a monotone one-task-job, this is more fulfilling and raises their own qualification. Second, the more value adding operations they do, the more they feel that they are actually building something, this is coupled with a sense of responsibility for the product and raises self-esteem and motivation.
- Finally, a very high system productivity can be reached, near to a full 100%.

There are however a few requirements that need to be met for this to work:

- **Process**: for a circulation cell to work the process needs to be clearly defined, linear and operator-oriented. If this is not possible, a possible solution is connecting more workcells together. It must also be possible to divide the work into parts along the stations.
- **Employees**: the operators need to be able to carry out all the tasks in the cell. This will probably require extra training. If there are special work tasks that require special qualifications/skills that not all workers have, then this can be a prohibiting factor.
- **Product**: the product must be able to move from workstation to workstation as fast as the operator walks. In simple terms this means that the operator should be able to carry the workpiece without physical strain. If not, it is still possible to design a matching transportation system.

Next best solution: “Baton-touch”

If for any reason the circulating job assignment is unworkable, the “circle” needs to be broken up into parts. This is called baton-touch. In this case one operator completes a few tasks in sequence, for example 1, 2 and 3 and then returns to the start and carries out this same sequence. If the cell is U shaped, with the two sides close by, then operator #1 can cross over to the other side as well, and do for example tasks 1, 2, 3 and then 9 and 10, then operator #2 does 3, 4 and 8 and operator #3 does 5,6 and 7, see *Figure 10*.

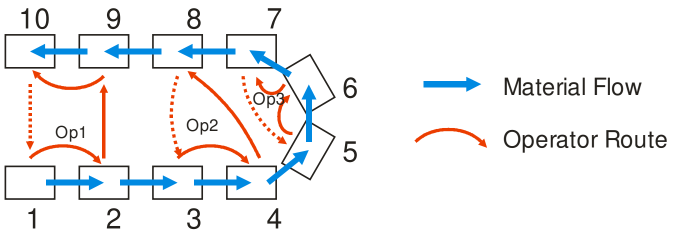

Figure 10: Baton-touch example with three operators in a U-cell.[83]

When assigning the tasks to the workers, the following points should be considered:

- In this type of organisation, the task times need to be added up for each operator, so that each one is below takt time. The smaller the takt time is, the more operators are needed.
- The times also need to be balanced well between the workers, this will curb conflicts and raise motivation. In the figure below, "3.7 operators" would be needed according to the equation, this is rounded up to four. Baudin mentions, that if this can be balanced in such a way that the last person has some free time, then this person *"acts as cell leader, feeding work into the cell, relieving others as needed, filling out the paperwork, etc."*[84], see *Figure 11* below. Other ways to solve this rounding problem have been discussed in *Section 2.5.5* on Takt Time.

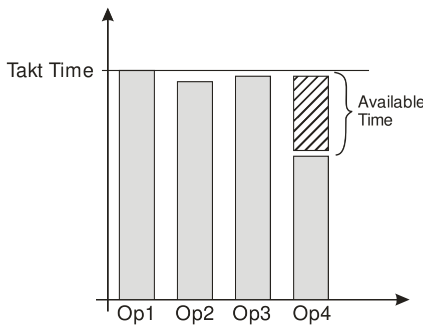

Figure 11: Operator loading.[85]

- The qualifications or skills of the operators need to be matched to their tasks. It is however a part of lean to raise the qualifications of the employees, so it is helpful if all operators are able to carry out all activities in the cell.
- The routes of the operators should not cross, i.e.: it might be a good division of labour for someone to do tasks 1, 3 and 5, while the second worker does 2 and 4, but their lines cross, creating problems in practice.

[83] Source (modified): Baudin, 2003.
[84] Baudin, 2003.
[85] Own diagram.

Alternative: "Bucket Brigade"
This is a different system lacking fixed job assignments, with several benefits. Requirement is that there are more operators, with the slower ones situated at the beginning and the faster ones at the end. The basic idea is that *"every time a unit is finished out of the cell, each operator takes over the next unit from his or her predecessor, and the first operator starts a new work piece"*.[86] This type is self-balancing, so that everyone tends to take the same amount of work.

2.7 Lean Phase 4: PULL

The fourth phase in lean implementation is called the pull phase. "*Pull in simplest terms means that no one upstream should produce a good or service until the customer downstream asks for it*".[87] In practice, it means that a "customer" – be that the real end user, a customer company or simply the next process – pulls the needed products from a WIP stock, while this stock is checked at regular intervals and replenished as needed by the previous process.

Types of Pull Between Operations:

2.7.1 Continuous Flow Process

As discussed before, a continuous flow is the preferred, ideal system. If it is possible to connect a number of operations so that the product flows without stopping, then:

> *"There could be immensely complex sub-processes involved, but as long as the thing being processed does not stop flowing for more than a few seconds - the entire process is depicted on a value stream map as a single Continuous Flow Process Box."*[88]

2.7.2 FIFO lanes

The term FIFO, meaning first-in first-out, is used in several areas, such as warehousing to rotate stock, or in accounting to calculate the cost of inventory.[89] A FIFO lane is a

> "*chute that can only hold a specified amount of items. When the chute is full, the supplying process stops producing until the downstream process finishes "digesting" the items in the chute, and there is room in the chute again.*"[90]

[86] Baudin, 2003. For more detail, see: http://www.isye.gatech.edu/faculty/John_Bartholdi/bucket-brigades.html
[87] Womack & Jones, 2003, p. 67.
[88] Systems2win: Glossary of Terms for Lean Process Improvement.
[89] Chaneski, Wayne S.: FIFO lane helps job shops regulate work flow, Center for Manufacturing Systems, New Jersey Institute of Technology, Newark 2004, http://findarticles.com/p/articles/mi_m3101/is_7_77/ai_n8686436/ (accessed on: 27.08.2009).
[90] Systems2win: Value Stream Mapping Training Concepts.

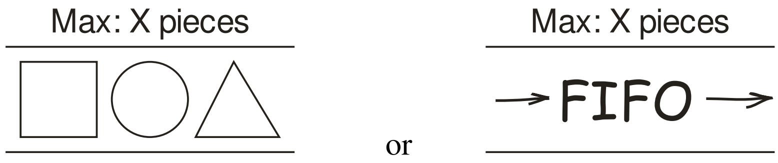

Figure 12: Standard VSM symbols for a FIFO lane, where X is the number of slots in the lane.

It is loaded from the back and emptied from the front, thereby keeping to the first-in first-out principle. Physically it is usually sloped toward the downstream process, so that the parts slide or roll down. It is also made in such a way, that it is impossible to take anything out other than the very last part. The central idea is that different parts and products use the same one FIFO lane, independent of the variant being made. This keeps the number of WIPs limited between each step, irrespective of the number of variants being made.

If continuous flow isn't possible, this is the next best method. The benefits are:

- The FIFO lane can "absorb" the variations in the cycle time of one process or differences in cycle times between the upstream and downstream processes.
- It prevents any inventory from piling up because the previous process produces faster then the next, since when it is full, a signal tells the upstream process to stop. This prevents overproduction, one of the seven deadly wastes.
- It can be used in high-mix but low-volume ("*HMLV*") production, since it doesn't drive the inventory up as kanban or supermarkets would.

Area of Application

These benefits also determine where it is especially a good idea to set up a FIFO lane. Particularly in applications with high product variety will it deliver a higher benefit as opposed to supermarket/kanban. If variations or differences in cycle times are preventing the introduction of continuous flow, then FIFO is the best solution. There are also requirements, see the requirements of a flow system in *Section 2.6.2*. The given situation must be examined. Other areas of application include the point where multiple value streams meet before product customisation or the point before some batch-operations.[91]

An example when FIFO wouldn't work can be a batch machine, for example a paint booth that cannot be downscaled. Although there is a WIP that could provide the required buildup of a batch, the problem is that different products could be in the lane, that need to be painted in different colours.

> *Note*: FIFO is not PUSH! The difference is that in a push system all processes produce to a master schedule, usually computed from forecasts through an MRP based computer program, irrespective of the following processes. A flow line however uses a single scheduling point at the beginning.

[91] Tapping et al., 2002, p. 65.

2.7.3 Supermarkets

A supermarket is a store of inventory between processes with standard maximum amounts of different parts, much like a real supermarket, where the customer takes the parts needed from the shelf. The American supermarket was in fact the inspiring starting point for Taiichi Ohno for developing the new system of pull and Just-in-Time, although he himself had only visited such a supermarket in later years.[92]

In regular intervals the supermarket is checked, if something has run out – like an empty shelf in a real store – a signal is sent to the upstream process to produce more. This signal is usually a production kanban, discussed in more detail in the next section.

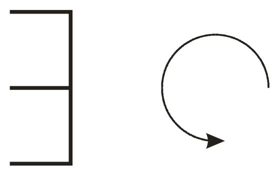

Figure 13: Standard VSM icon of a supermarket.
Note that the open side faces the upstream process, which needs to refill it, while the pull arrow is on the downstream side.

Area of Application
Supermarkets are good to use between processes that cannot be run in flow. Since the supermarket is controlled by the downstream – that is, customer – process, a supermarket for works in progress can only be placed upstream relative to the pacemaker process. Supermarkets for all other parts can be placed at any given operation.

One important requirement is not to store too many parts in the market, as it drives inventory costs up. Since this is problematic in HMLV applications, possible alternatives are:

- Moving the variety-adding step downstream (compared to the supermarket). This can lead to enormous savings in bound capital. Let us take a metal part as an example, which has the same basic shape, but with holes that need to be drilled in different ways for 20 different products. If the drilling operation takes place before the final assembly, and there are 40 parts per supermarket shelf, then the inventory is $20 \cdot 40 = 800\ pieces$ and 20 shelves are used up. With a cost of \$15/piece this gives us \$12000 in inventory between two processes. If we move the drilling step forward to the start of final assembly, only the base metal part need be stored, using up one shelf and only $\$15 \cdot 40 = \$600$ in stock.[93]
- Moving the pacemaker process upstream, and replacing the supermarket with a FIFO lane. Now the orders are scheduled more upstream, the FIFO lane limits the WIPs and the downstream process assembles every time exactly what comes out of the lane.

[92] Womack & Jones, 2003, p. 37.
[93] For another calculation, see: Weber, 2004, p. 37.

2.7.4 Kanban

> *"Kanban: An inventory control card at the heart of a pull system. The card is a means of communicating upstream precisely what is required (in terms of product specifications and quantity) at the time it is required."*[94]

This is the original, narrow meaning of the Japanese term *kanban*: a pull signalling card. It also stands for a whole material flow control system based on kanban cards, using the pull principle and JIT. From an even wider perspective, it is a complete philosophy related to and used widely as part of lean. It can bring huge benefits but requires much discipline. For a successful deployment of a kanban system all departments and all employees need to be involved and motivated.

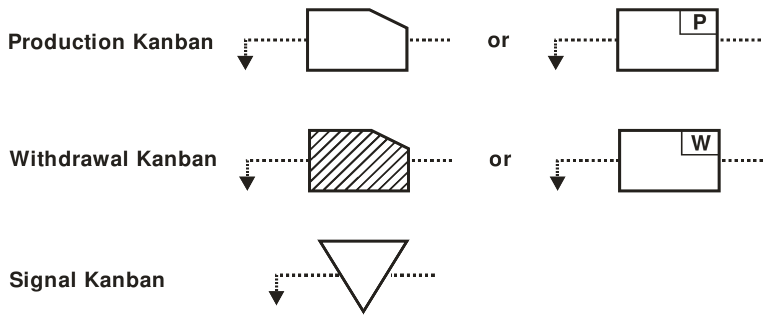

Figure 14: Kanban VSM symbols.

The application of kanban inside an enterprise can be divided into three areas: *supplier-kanban*, meaning the suppliers ship in a kanban system (*"loop"*), either into the warehouse or directly to the line. *Production-kanban* is used in the value stream inside the factory, while *customer-kanban* means the company ships its customers in a kanban loop.[95] The central idea coincides with that of pull, some authors even use kanban as a synonym for a pull system, this paper will however make the distinction: pull is the idea of pulling products from a small stock, and only producing when the stock needs to be refilled. Kanban is then a special case of a pull system, a means of controlling upstream production, with the rules described below.

How it functions

Kanban is in itself very simple and easy to understand. It can do in a markedly simple way what a refined planning algorithm in an expensive MRP software does, but more effectively, faster and with lower costs. A basic example can be an assembly line of small products. Let's suppose there is a simple electronic component, a small circuit board, that is needed for this product, which is manufactured in the same building by a separate machine. There is a box full of these circuit boards at the assembly cell. When it runs out, a card attached to the box is sent to the circuit board machine, which manufactures exactly one boxful of parts, this is sent

[94] Tapping et al., 2002, p. 150.
[95] Weber, 2004, p. 8.

back to the downstream process. Now it is logical, that in order to sustain continuous production, at least two containers are needed, while one is being replenished the assembly can work from the second one. These two – or more – containers form one kanban loop.

While this is the simple basic way of operation, the system needs several elements to function, inluding a stockpoint or buffer with the containers, either at the source, at the destination or in-between. A withdrawal signal is also needed, these are the actual kanbans (cards), usually a printed sheet with a number of data on it or an electronic signal. For several reasons, the container is not used as a signal – although an empty container could function as such. Furthermore, immediate feedback and frequent replenishments characterise the system.

> *Note*: The subject area of kanban is a very wide field, there are a number of books, theses, articles on the matter, please refer to these for more detailed discussions.

There are rules that must be kept for the whole system to work. If these are not properly enforced, then kanban will not achieve its potential.

- *"Downstream operations or cells withdraw items from upstream operations or cells.*
- *Upstream operations or cells produce and convey only if a kanban card is present and only the number of parts indicated on the kanban.*
- *Upstream operations only send 100-percent defect-free products downstream.*
- *Kanban cards move with material to provide visual control.*
- *Continue to try to reduce the number of kanban cards in circulation to force improvements."*[96]

The main characteristics and through these the benefits of a kanban-pull material flow system are:

- It accomplishes pull, as the upstream operation only produces when the downstream one needs more material. Wastes associated with non-pull solutions are reduced or eliminated, such as overproduction, excess inventory, excess movement of products and lack of flexibility.
- There is some inventory between each step, where the maximum stock in a given loop is:

  $$max.\,stock\ in\ loop\ = cards\ in\ loop \cdot units\ per\ container$$

  This means it is not the perfect, ideal solution, but until a pure continuous flow can be achieved, it works well.
- Employment of kanban in the company leads to decentralisation and a higher responsibility for the workers of each cell, which is a motivating factor.
- If there is a problem in the manufacturing system, then the kanban loop stops, stopping production. One must seize this as a chance and using problem solving methods, such as the Five Whys, Ishikawa Diagrams and others, solve the problem ASAP.

[96] Tapping et al., 2002, p. 65.

Kanban is however not an omnipotent solution as some sources might say. There are disadvantages as well. For one, as mentioned above, small problems in the system can cause system stoppages, which, while revealing problems, do stop the whole assembly line. The flexibility is also not ideal, as it operates with a fixed transport batch since there need to be an integer multiple of the containers.

Kanban Signalling in Pull Systems

Kanban signalling is very often used in all types of pull systems. A supermarket also uses such signal cards to signal upstream production. Therefore to make a distinction, from here on a supermarket will refer to a collection of parts and materials in a rack, just like in a real supermarket, from which the operators decide – based on their work order – which part to take. Kanban will then refer to all other kanban-signalling solutions, such as separate parts containers at the assembly stations.

Areas of Application

As previously mentioned, kanban is no one-solution-fits-all and therefore each time it must be checked to see if it is the right solution. For WIPs, kanban needs to come before the pacemaker, for purchased parts supplied to the assembly line this is unimportant. Basically *"the technique can be applied to any pair of resources, or pairs in a series of resources (including clerical operations), where one feeds the other."*[97]

2.7.5 Kanban Variants[98]

Simple Versions: 2 Bin and 3 Bin Systems

Two bin and three bin supply systems have existed independent of kanban for years. In the two bin system, bin #1 is in the shop being used, while #2 is somewhere else (warehouse, supplier, etc.) and is used to replace bin #1 when that is depleted. Then #1 is taken away to be filled, while #2 is being used. The three bin version has a separate third bin with a safety stock that is only used in an emergency.

One Card System

There is one signal used per loop, sent from the consuming process to the supplying process, and having two meanings: "Send more material (one transfer batch) from the buffer stock!" and "Produce more to the buffer stock!". Used when the two processes are close by.

[97] SM Thacker & Associates: Kanban Systems, 2009.
[98] Based on SM Thacker & Associates: Kanban Systems, 2009.

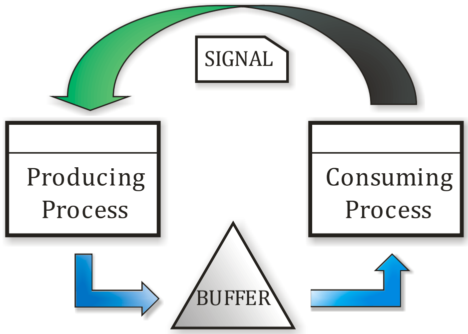

Figure 15: One Card Kanban.[99]

Two Card System

Since this is basically the "standard" kanban system that is most widely used, its function should be examined more closely. There are two cards in the loop, decoupling replenishment and production.

- A production kanban indicates that a buffer needs to be filled up by the producing system. It accompanies the product through the process from the initial to the final buffer. When the product is taken from the buffer to the next process, the kanban is placed in the kanban receiving post, and then taken to the ordering post, where it waits for its turn with the other kanbans in FIFO order. When it is next, the part specified on it is processed, including withdrawing the necessary parts from the initial buffer.

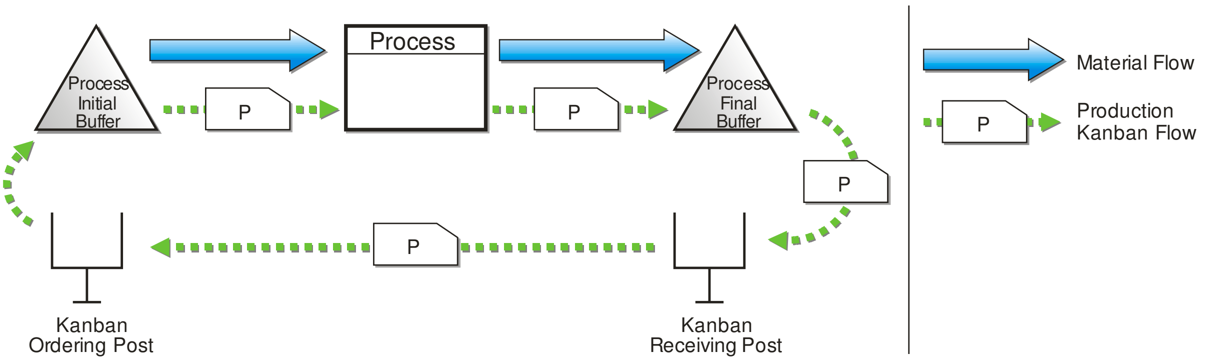

Figure 16: Flow of production kanban.[100]

- A withdrawal kanban indicates that a process needs replenishment from the buffer. It is taken to the output buffer of the supplying process, accompanies the container back to the downstream process and is then put into a kanban post when the container is used up.

[99] Based on: Ibid.
[100] Based on: Tufecki, 2009, p. 1.

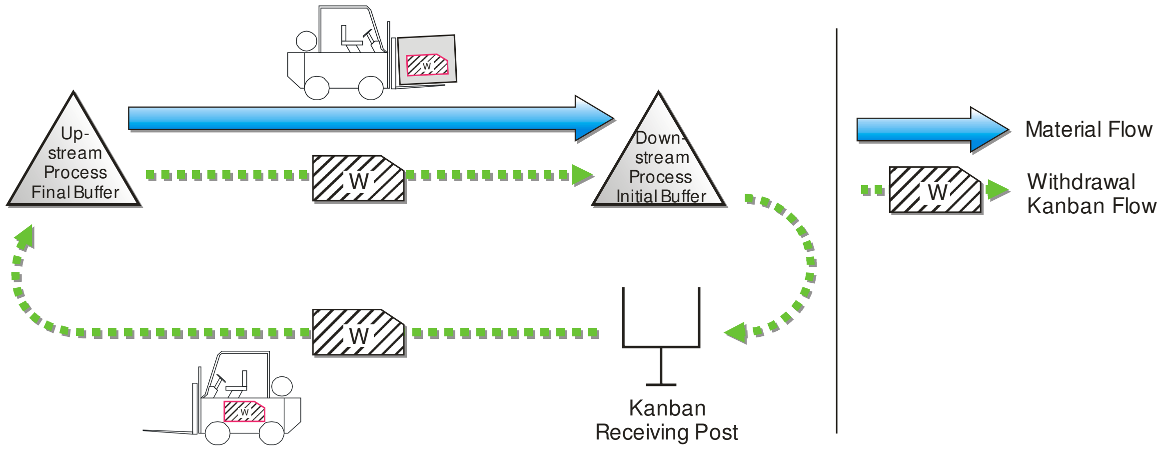

Figure 17: Flow of withdrawal kanban.[101]

- There is a third type of kanban: the signal kanban. This is used when the supplying process must run in batch mode, for example because of long changeover times. In this case, the signal kanban is used to withdraw one batch from this process.

Kanban Accumulator

In this version, kanban cards are allowed to accumulate at the supplying resource until a production batch size is reached.

ConWip (Constant Work in Process)

ConWip is a variant that has gained popularity, among others for its ease of implementation and low WIP levels. The idea is that the whole production system functions as one large kanban loop. As soon as one product (one container) is finished and leaves the system, a signal is sent to the first process to start a new product, irrespective of the type of product, as the cards are shared. The effect is that the sum of the works in progress in the whole line is limited.

Variable Quantity (Fixed Frequency) System

While multiples of constant quantities are used in kanban supply loops, this variant works by refilling the buffer to a prescribed level in fixed time intervals. Such a solution is often used when suppliers fill up the customers' stocks at the point of use.

Others

Over time several other systems have emerged, some have been widely accepted, others less so. Some, such as the PAC (Production Authorization Cards) are able to work both as pull and as push systems, depending on how the system parameters are set. This thesis is not the place for an in depth analysis, please refer to the literature.

[101] Based on: Ibid., p. 4.

eKanban
As with many methods today, kanban has also been implemented as an IT solution, called eKanban. The literature itself is divided, some authors commend eKanban as a necessary next step, having benefits such as faster signal transfer, easier reporting and no lost cards. Others argue that the marginal benefits it brings are not worth the additional cost of implementation and administration. Most seem to agree however, that the benefits are mainly realised only in material transfer between firms over long distances, while inside the factory the advantages are minimal.

2.7.6 Levelling Production

Since customer demand varies from day to day, precisely following the customers would lead to an erratic production that would need to start and stop frequently. This causes the so-called bullwhip effect, which travels upstream and introduces ever more fluctuation. A lean factory is however characterised by a consistent and therefore efficient material flow, flowing to the rhythm of takt time. This requires levelling production.

The basic premise of levelling production is that while customer orders vary in the short-term, they are really mostly constant in the long term. A sound understanding of the long term demand serves as basis for levelling. As this topic falls outside the scope of material supply and material flow, it is only shortly described here for sake of completeness, details should be sought in the literature.

Heijunka

> *"Production levelling is based on orders analysis (products and volumes mix) in a given time span (one month, for example) in order to find out a pattern fitting in a smaller time span (daily, for example). This pattern is to be repeated until the whole demand (of the month) is satisfied."*[102]

This means that the demand is summed up for a longer period, e.g. one month, for example: 800 units of product A, 400 of product B, 250 of products C and D and 100 of E. This gives a ratio of $A:B:C:D:E = 16:8:5:2:2$. The same ratio as the demand is then replicated in production in a smaller time span, for example one week. This means that the available production time in one week is divided into 16 parts for product A, 8 parts for B, 5 parts for C and two parts for D and for E, and scheduled to the pacemaker process in this way. This smaller interval is also called the EPEI or Every Part Every Interval.

Levelling production means lowering the EPEI interval as much as possible. The limit to this is the changeover time, since lower EPEI's mean frequent changeovers. A low EPEI means

[102] Hohmann, 2008.

that the clients can be shipped quickly as they don't have to wait for the next interval to produce the products they need. Lead time is reduced, so is WIP inventory and therefore storage space. Flexibility is increased and surges in demand are levelled.

This method is called *heijunka* and is physically controlled through the *heijunka box*. This is a board with slots in it, each slot representing one pitch increment in time, see *Section 2.5.6 Pitch*. One Kanban card is placed in each time slot so that in the whole EPE Interval the ratio of Kanban cards for e.g. products A, B, C, D and E is equal to the ratio of demands. Note: errors in rounding to whole pitch increments need to be resolved by adding/subtracting an extra card once in a while.

2.8 Lean Phase 5: PERFECTION

One of the central ideas in lean is continuous improvement. If the company has gone through the planning stages described in this paper and implemented the envisioned future state, it should not sit back in self-praise. For one, any improvements made to the system will not remain on level by themselves. Things have a way of running down and deteriorating when left to themselves. **Discipline** is required, which is an important cultural difference between the birthplace of Lean – Japan – and the Western world and is frequently cited as one of the reasons of failed lean implementations.

On the other hand, even if manufacturing is kept at a constant level, one can never relax, while the competitors might just be planning or implementing a better system; the system needs to be improved constantly. To be able to constantly improve processes, a "vision of perfection" is needed, i.e. what the ideal state is, with no waste, no non-value-adding activities, a levelled production that can always produce to customer demand – that is, follow takt time – perfectly in 100% quality and minimal costs. Without such a vision, one can be content with "good-enough", but lean thinking encourages such a **vision of perfection** and constant movement in its direction. There are two widespread improvement methods:

2.8.1 Kaizen

> *"...the philosophy of continual improvement, that every process can and should be continually evaluated and improved in terms of time required, resources used, resultant quality, and other aspects relevant to the process."*[103]

In practice, so called *improvement workshops* (also called *kaizen blitz* or *kaizen events)* are carried out in small groups to find and implement possibilities for improvement. The members of the group – mostly operators and other line workers – focus on their own work

[103] The Northwest Lean Networks: Lean FAQ's, 2009.

area or area of expertise. Very often, such workshops are used for realizing new factory layouts or work procedures, they are also used in the concrete implementation of lean manufacturing, see *Section 5.10*.

2.8.2 Kaikaku

As opposed to the small improvements over time achieved through kaizen events, kaikaku refers to large, radical changes or reengineering. These are usually carried out by managers and engineers, as workers would not have the required overview, authority or access to resources.

Chapter 3 – Factors

Before examining the existing planning methods, it is expedient to sum up the different factors and criteria that influence the planning of an assembly line material flow. There are physical and non-physical factors; constant and variable factors; planning input factors as well as outputs (goals) of the project. The most important ones are discussed below.

3.1 Physical Factors

The more readily available or more easily measured characteristics are the physical ones, they usually influence both general planning as well as detail planning, such as the number of parts stock per workplace or the number of kanban cards in a loop. Physical factors are also very important in transportation planning, which lies outside the scope of this thesis. The more important ones, approximately in order of decreasing importance:

- **Size** (dimensions) and **weight**: the basic physical properties of the materials and parts. These influence the type and dimensions of the warehouse(s) used as well as the transport methods and vehicles. Small parts can be stored in a revolving small-parts-rack, large ones must be stored in a several storey warehouse. Light parts have little influence on the transport method, while the movement of heavy parts must be planned carefully and minimised as much as possible.

- **Shape and Design**: The form can also have an influence, especially if it is unusual – i.e. not cube-like – such as long, thin parts, for which special storage racks must be used. A property derived from the form is the **stackability**, that is, can the parts be stored on top of one another and how many can be stored in such a way. If *Design for Assembly* (DFA) is taken into consideration during product planning, the material flow costs can be *a priori* reduced, for example through less transportation, organisation, manipulation of the parts.

- **Logistical Properties**: size and shape of the containers and the number of units per container. Influences the detailed planning, such as number of kanban cards in a loop.

- **Number of units per package (inbound side)**: this influences the number of parts that can be ordered at once. It is possible that only whole packages can be ordered, in this case the order quantity must always be a multiple of this number. On the other hand, it might be possible to order smaller quantities, then it only affects transportation.

- **Transport distance**, which applies to all three areas: inbound logistics, shop-floor logistics and outbound logistics. This is less important for the current topic, and will not be discussed in more detail.

- **Empty packaging**: the costs of the empty packaging (transport, recycling) as well any possible further uses should be part of the planning calculations. Standardisation is a cost saver, good examples are pool palettes (e.g.: EUR-Palettes) and standard boxes.

3.2 Non-physical Input Factors

3.2.1 Demand

This is probably the most important factor for manufacturing/assembly or the enterprise as a whole for that matter: **demand**. The main goal of most companies is to measure the demand for its products and try to meet that demand, otherwise the product or service will not be sold – not forgetting of course, that demand can also be created or changed with tools like marketing. The demand for the existing as well as possible future products should be understood and as much as possible quantified. This is one of the main factors when planning the material flow, the following being some of its important characteristics:[104]

- Demand of the market/customers on **mass products**, **special products** and **replacement parts**. A demand profile can be constructed with sub-criteria such as: variability of the products, number of units per sale, how often it is bought, what percentage does product play in sales according to value/weight/etc.[105]

- Demand is made up of three parts:
  - Primary demand: what the customers are willing to buy from the company.
  - Secondary demand: all the materials and parts needed to manufacture the primary demand.
  - Tertiary demand: all other materials that are needed, but do not constitute a part of the final product.

  Gross demand = primary + secondary + tertiary demand
  Net demand = Gross demand – available stock

- The point at which the products are along their respective **lifecycles**. Whether a product is at the beginning of its lifecycle or nearing its end should be considered in planning, as it requires different strategies.

- The "**forecastability" of demand** influences which control method should be used. This factor can be calculated for past periods by comparing the previous forecasts with the actual demand.

[104] Dickmann, 2007a, p. 156.
[105] For an example demand profile, see: Dickmann, 2007a, p. 156.

3.2.2 Classification Along Further Criteria

There are a few widespread classification techniques to simplify planning projects. The parts or materials are classified according to two criteria; they are arranged in sequence according to one criterion and then divided into (usually) three groups. The most frequently used techniques are presented here, see the ample literature for more information.[106]

ABC-Analysis (of parts): Value and Sales Quantity

The ABC-analysis is the most widespread, products are divided into three groups according to their value and sales quantity. The A-parts make up about 10-15 % the quantity of sold goods, but 80% in terms of value, the B-s are less valuable but more plentiful, while the C-parts are bulky and cheap. During different types of planning, the A and B parts receive the most attention, since relatively small changes mean big savings. However, for the material flow all the parts, including the C-parts, must be addressed; if needed, each type with a different method.

UVW Classification (of suppliers): Reliability of Delivery

Inbound logistics provides the UVW classification: U-suppliers deliver goods punctually, almost always on time, they are reliable. V-s are less reliable, while with the W-suppliers one can never be sure if they will deliver on time. This is especially critical, since one missing part means the whole assembly operation stops, this must be addressed in advance during planning.

RUS Classification (of parts or materials): Variability of Order Quantity

This method shows the variation of the quantity picked from the warehouse for each given part. The R-parts are picked in regular amounts, the U-s are more irregular, while the S stands for stochastic, this type cannot be predicted.

XYZ Classification (of parts): Variability of Order Frequency

The second attribute of warehouse output is the variation of the frequency of demand for one given part. X-parts are picked at a constant rate, Y-s are not, but follow general trends, while it is completely unpredictable when a Z-part will be needed.

These four classifications, as well as any other internal classification that makes sense can be used to divide the parts into groups to help in material flow planning.

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[106] See: Lotter, Wiendahl, 2006, p. 329.

3.3 Objectives

This group of factors is not an input for the planning but the desired outcome and as such also influences the planning stage. Some of the important factors here are:

Bound capital: capital is bound in the material flow system: in the warehouses, the transport vehicles, but most of all in the three kinds of stock:

- Input material and parts, after they have been paid for,
- Work-in-process parts and
- Finished goods stock, until they are bought and paid for.

If we plot the increase in value of a part along a timeline from purchase till sale (simplifying it as a straight line), the trapezoid area under the plot is the capital bound, measured in [money unit]·[time unit].[107]

$$Capital\ Bound = Lead\ Time \cdot \frac{Sales\ Price + Purchase\ Price}{2}$$

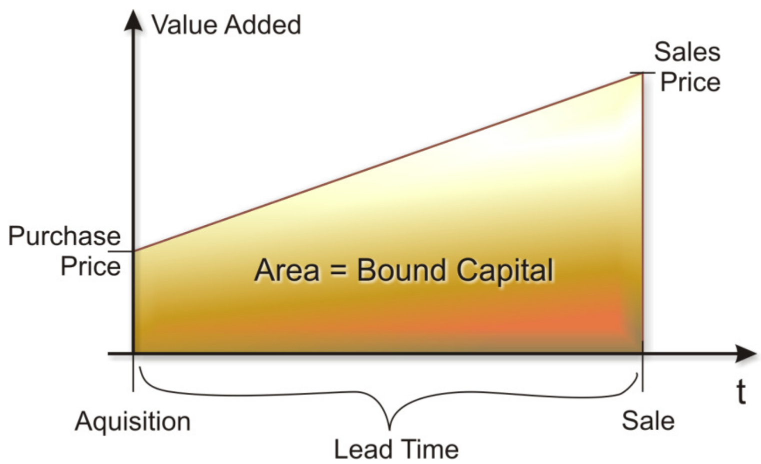

Figure 18: Bound Capital.[108]

Costs: as in all parts of a corporation, the costs must be reduced as much as possible. The different internal processes are however so much interrelated, that reducing costs in one department might increase the costs of another, therefore instead of one-sided cost reduction in one given area (local optima), a proper planning method should consider other areas and strive to reach a common optimum.

The classical way to calculate logistics costs was to count them as overhead and then using overhead rates allocate them to the products. This is an unclear method, the cost triggers

[107] Koether, 2001, p. 3.
[108] Figure based on Koether, 2001, p. 3.

cannot be identified easily; there is the more modern process of activity-based costing, in which the costs of the different logistics activities are calculated, for example *"one day in warehouse A"* or *"load palette"* or *"pick parts to order"*.[109] It is not a perfect method and other ones also exist.[110]

Flexibility is *"the ability of a system or facility to adjust to changes in its internal or external environment."*[111] The objective is to increase the flexibility of company operations. A well planned material flow should lead to flexibility in meeting differing customer demands, where the differences can be in regard to the number of units sold, the types, any special wishes of the customers, delivery method or times and so on.

The **Lead Time** is the elapsed time from parts entry till sale of finished product. A high lead time has many adverse effects, such as lowered flexibility, higher capital binding, higher warehouse costs, etc. and must therefore be lowered.

The **Service level** is *"a measure for the extent to which the customer orders can be executed at delivery conditions normally accepted in the market."*[112] This should be maximised as much as possible, though 100% is inadequate, as that leads to excessive stock. A compromise must be made and a "good enough" service level somewhat under 100% decided on.

Quality is today such a requirement, that it is not an influencing factor, it simply must be ≈100%.

This was a selection of the most important factors and parameters. There can be an indefinite number of other factors which might come into play under different circumstances but these are of minor importance in the general material flow planning methodology and will only be discussed at the appropriate planning step. The factors above discussed also serve as a basis for the literature review and evaluation of the different planning methods in the following chapter.

[109] Ibid., p. 3.
[110] For more on activity-based costing (ABC), see: http://en.wikipedia.org/wiki/Activity-based costing
[111] Das, 1996, p. 67.
[112] The Shipping Department of Francoudi & Stephanou - SHIPPING : : Terminology, http://www.shipping.francoudi.com/main/main.asp?cm=14&letter=S (accessed on: 08.08.2009).

Chapter 4 – Literature Review of Methods

This chapter aims to list and examine the planning methods that can be found in the current literature. As of writing, no single method could be found that covered the thesis topic in its entirety. The methods that can be found have different scopes and build on different fundaments: some focus on assembly, some on material flow and some on just one smaller aspect of these topics.

4.1 Methodology

To make the different methods comparable, they are presented in a uniform format. First the source and a short thematic classification is given, illustrating the basis of the method. Then the main steps and the central ideas are described. This is followed by the factors covered by the planning method. Finally the relevance to the specific thesis subject and the pros and cons are examined.

The following topics are covered by at least one method, most of them cover several. The topics in bold are the subjects of this thesis.

- Suppliers: the part of the material flow outside the company, inbound side.
- Purchase: how and when to order material.
- **Inbound warehouse and picking**: what happens when the material arrives, how to store it and how to pick the necessary parts from the warehouse for assembly.
- Transport: all internal transportation.
- **Material delivery**: how to deliver the materials / parts to assembly.
- **Control**: how to control the internal logistics, what strategies to use.
- Assembly layout: detail planning on how to organise the workspaces, machines, tools, parts and workers.
- **Material flow in assembly**: flow between workplaces.
- Sales and shipment to customers: the part of the material flow leaving the company on the outbound side.

4.2 Method A – Conventional Planning

Source: Based on Eich, B.; Schneider, B.: Planung der Teilebereitstellung in iwb Seminarberichte – 13 – Planung von Montageanlagen.[113]

Category: assembly based.

[113] Eich, 1995, pp. 93-95.

Description: The information for the assembly line planning is collected, including:

- Product information:
    - Assembly sequence and parts characteristics
    - Joining techniques
    - Product versions
- Production information:
    - Times and quantities
    - All other requirements for using a machine / a cell / a workplace

From this an assembly concept is developed and then every step in the material flow planning is based on this finished plan. All the requirements for the material flow are now predetermined and cannot be influenced any more: where each machine, cell or workplace needs to receive its materials, how much, in what orientation with what tolerances, etc. The material supply must now satisfy all of these separate demands, including a lot of handling, sequencing, reorienting and transportation, all non-value adding activities, therefore *waste*.

Factors covered: only the production/assembly related factors are taken into account.

Relevance: This method covers in reality none of the important subjects, it was only included as it shows a conventional, purely assembly-based planning process.

The same author then also provides a new and corrected model:

4.3 Method B – Designing a Linked Process Chain

Source: same as above.[114]

Category: process and cost-reduction oriented.

Description: During the planning and layout of the assembly line, the inputs and outputs of the workplaces and their connections are taken into account, as well as the whole process itself. The costs of all process steps, including the logistics steps are plotted on a chart, whereby the process costs are divided into main processes and auxiliary processes. Then the whole assembly is cost-optimised, by reducing the number of auxiliary processes, as well as the costs of the main processes.

Some possibilities for optimization, selection of the one to use is based on process costing[115] calculations:

[114] Ibid., pp. 96-103.
[115] For more on process costing, see: Process Costing :: Characteristics, Features, Application in Industry, http://www.futureaccountant.com/process-costing/study-notes/characteristics-features-application-industry.php

- Make the flow of materials easier, e.g. use magazines.
- Change the order of steps, e.g. move some production steps downstream, into assembly.
- Integrate steps in one workplace, making transport unnecessary.

Factors covered: process costs based on space and time requirements. From the objectives, costs and time are covered, flexibility and service level aren't.

Relevance: The material delivery to the workplace is relevant, and the cost-optimisation is useful. Little is said however about the actual planning (what to optimise?).

4.4 Method C – Material Supply According to Nyhuis et al.

Source: based on the chapter *Materialbereitstellung in der Montage* in the book *Montage in der industriellen Produktion* by Lotter and Wiendahl.[116]

Category: material flow based.

Description:
The assembly line is not planned in this method. Whether it is given or developed parallel with the material flow is not specified.

Before beginning to plan, a demand analysis is carried out: primary, secondary, tertiary, then gross and net demand are calculated (see *Section 3.2*). Product analysis methods, as seen in *Section 3.2.2*, are carried out: ABC, UVW, RUS and/or XYZ, to help decide on the supply method for each part, using the following table as a guide (with the original German expressions in brackets):

<table>
<tr><th></th><th>X
demand constant</th><th>Y
demand trend based</th><th>Z
demand erratic</th></tr>
<tr><td>A parts</td><td colspan="2">purchase synchronized with demand
(Just in Time)
(“bedarfssynchrone Beschaffung“)</td><td rowspan="2">individual purchase based on actual demand
(“Bedarfsfall-bezogene Einzelbeschaffung“)</td></tr>
<tr><td>B parts</td><td colspan="2">purchase close to demand
(~JIT)
(“bedarfsnahe Beschaffung“)</td></tr>
<tr><td>C parts</td><td colspan="3">purchase to warehouse
(“Vorratsbeschaffung“)</td></tr>
</table>

Figure 19: Decision matrix for supply strategies, based on ABC and XYZ classification of parts.[117]

[116] Nyhuis et al., 2006, pp. 323-344.
[117] Based on: Nyhuis et al., 2006, p. 331.

Then the planning takes place, the first step of which is the warehouse, based on the following types and purchasing strategies:

- Company owned warehouse, with all inherent costs:
    - Warehouse procurement, which is usually good to avoid, as it disconnects the purchase from the production. It is only recommended in this method for C-parts.
- Supplier owned warehouse:
    - Standard parts management: the suppliers are responsible for the supply of standard parts.
    - Consignation concept: a supplier owned warehouse is located at the production site, for example a part of the same building is rented.
    - Contract warehouse: supplier warehouse located close to production, with quick shipping, e.g.: JIT.
- No warehouse:
    - Individual procurement: only when demand exists.
    - Synchronized production processes, without a buffer between producer and supplier.

Next step is the material delivery between warehouse and workplace, which constitutes two main steps: "picking" and transport. Picking (selecting and taking out parts from the warehouse) can happen in different ways:

- Order picking: pick everything for order #1 then order #2, etc.
- Parallel picking: pick all the materials for more orders and then sort.
- Pick according to material.

A number of optimisation strategies for warehouses and picking are given, see source.[118]

Then the value flow control is developed, with the basic principle of as much self-regulation as possible, as it improves transparency and lowers costs. The criteria for the selection of the proper control method are the physical parts, handling and logistical properties. There are two main types of material supply:

- Controlled by use: useful for A, B or C parts, but not the seldom used exogenous parts. The best known variants are *kanban* and *supermarket*. They are always based on pitch size.
- Controlled by demand: useful for A-parts with extremely high value, when the main goal is to minimize the inventories. The size can be a pitch or an exact amount. Examples are JIT and JIS (Just in Sequence).

The final step is the detailed planning of the material delivery, different strategies being the conventional (transport in pitch sizes, e.g. EUR-palette), order-based, kanban, setwise or manual warehouse. A so called "milk run" is widespread.

[118] Nyhuis et al., 2006, pp. 338-339.

Factors covered: mainly demand and product classifications (source for *Section 3.2.2*), the physical properties are just touched on.

Relevance: Very high, all the topics along the material flow are covered, excluding inbound and outbound logistics.

4.5 Method D – Value Stream Management

Source: Value Stream Mapping according to *Value Stream Management* by Don Tapping, Tom Luyster and Tom Shuker[119] is a lean method to transform the whole value adding operations of a company to lean, including inbound and outbound logistics, production and assembly.

Category: value stream / lean based.

Description:
The method contains eight steps, which guide the users through the analysis and redesign of a company value stream, the steps being:[120]

1. Commit to Lean
2. Choose the Value Stream
3. Learn about Lean
4. Map the current state
5. Determine lean metrics
6. Map the future state
7. Create Kaizen Plans
8. Implement Kaizen Plans

From these steps, the third and sixth are the most relevant, in step 3 the three stages of a lean transformation are discussed, while in step 6 they are used to plan the future state.

Stage 1: Demand: determine and meet
Concepts:

- Understand customers' ordering patterns,
- Takt time, Pitch, "Takt image": ideal state of one-piece flow
- buffer and safety inventories, supermarket (finished goods, WIP, etc.), lights out manufacturing, etc.

Steps:

1. Determine takt time, determine pitch (as: takt time x pack-out quantity)
2. Can demand be met with current methods? Determine actual capacity.
3. Do we need inventories? How much?

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[119] Taping et al., 2002.
[120] Ibid., p. 5.

    - Buffer inventory for demand fluctuations
    - Safety inventory for internal constraints or inefficiencies
4. If pure flow is not possible: a finished-goods supermarket.
5. Determine improvements and improvement methods (5S, SMED/QCO, autonomous maintenance, methods analysis, etc.).

Stage 2: Flow: implement flow

Concepts:

- Continuous Flow: “Move one, make one.”
- Pull system with as small batches as possible.
- Work Cells: do not group by equipment, but to reduce waste and promote flow.
- Other concepts: standardized work, quick changeover, autonomous maintenance, FIFO lanes, production scheduling.

<u>Steps:</u>

1. Perform line balancing (using: operator balance chart).
2. Plan for work cells.
3. Determine how to control upstream production:
    - In-process supermarkets
    - Kanban
    - FIFO lanes
    - MRP
4. Determine which improvement method to use.

Stage 3: Leveling: evenly distribute work over a shift or a day.

Methods:

- Paced Withdrawal
- Heijunka (load levelling)
- The runner: a “mailman”, for problem solving, moves parts or cards as needed.

<u>Steps</u>:

1. Decide method.
2. Decide route of runner, so that it is shorter than pitch.
3. Decide on improvement method(s) and all other data needed.

Wrap-Up

- Review and modify as needed.
- Determine metrics for future state.
- Thank the team for their efforts.

<u>Factors covered</u>: basically all, including all the objectives of flexibility, cost, lead time, service level and quality.

<u>Relevance</u>: Very high, the whole thesis subject is covered, it is however missing the specific details.

4.6 Method E – a mix of lean and innovative methods

Source: The book *Schlanker Materialfluss – mit Lean Production, Kanban und Innovationen* by Philipp Dickmann[121] contains articles from 48 experts, where a large number of different innovative methods (including planning methods) can be found. Although they are not described in detail, the book serves as a comprehensive overview of modern techniques and helps as a guide in selecting the best ones for a job. The relevant techniques are the following:

Category: mostly lean based methods.

4.6.1 Planning for Flexible Production[122]

Description:
The **first stage** is to determine the production capacity and plan a production/assembly line, using the following steps, whereby the similarity to the three stages of value stream management should be noted:

1. Determine the process times for all work steps.
2. Calculate the resources, based on demand, available time and lead times.
3. Spread and balance the work for a continuous flow.

The material supply and logistics are planned in the **second stage**:

1. Rework the bill of materials into one flat list.
2. Calculate the kanban material supply with average demand and acquisition time.
3. Define the material flow from the suppliers to the assembly line.
4. Define the decoupling points between supply and production. If a continuous flow cannot be guaranteed, so-called supermarkets must be used.

4.6.2 Control Methods[123]

Description: Possible control methods are overviewed:

1. **Demand based** (make-to-order), push principle: the orders arrive randomly, the production load is stochastic.
2. **Make-to-stock**: orders are shipped instantly from a finished goods inventory, while production ships to this inventory. Depending on how to produce to stock, the following variants can be differentiated:
    a. **Inventory based** (make-to-stock): when a given critical quantity is reached, more is produced to fill up the finished goods inventory again. Very widespread, kanban is such a system.

[121] Dickmann, 2007.
[122] Wilbert, 2007, p. 21.
[123] Dickmann, 2007b, p. 115.

   b. The classical push principle is used in the **forecast based** method, usually with MRP based planning, used in trade and production.
   c. The **load based** method tries to level the load on the different company resources, usually used in conjunction with other methods. Examples are BOA, OPT, Local Control, Integral Control, Constant WIP, etc.
3. Some generalized methods also exist, where the alteration of parameters changes the behaviour of the control system. For example Production Authorization Cards can be varied between fully push, fully pull or in-between.

4.6.3 C-parts Management[124,125]

Description:
Very often C parts are left out of the planning or optimisation processes in favour of the more expensive A and B parts, though a missing C part can mean a costly disruption in assembly. Planning the supply of C-parts must therefore be part of material flow planning. The above mentioned book provides two articles on C-part supply, please see there for a detailed explanation.

Factors covered: The above three sources cover different factors, but together they cover all, including all the objectives.

Relevance: High, the important subjects are covered, while picking, transport, suppliers and customers are not.

4.7 Method F – Kanban

Source: There are lots of sources on this topic. One example is from Rainer Weber: *Kanban Einführung*[126] which describes not only Kanban principles but also a complete lean makeover of a factory based on Kanban material flow.

Category: lean based.

Description:
The source describes an expansive method, covering many aspects of a company's transition to lean, including required personal and organisational changes. It is however weakly structured and not a practical follow-me guide, therefore instead of sequential *steps*, it only has main *elements*:

[124] Beer, 2007, p. 272.
[125] Graßy, 2007, p. 278.
[126] Weber, 2004.

An organisation change is first required, restructuring the factory into product or product group based teams (units). These are incorporated into the organisation with central and decentral responsibilities. Besides this, non-value-adding activities must be reduced.

The production is organised into lines or islands (cells), with examples given in both production and assembly. Reducing inventories is an important point, among its many uses it also exposes problems, which can then be solved.

To boost flexibility and be able to make many variants, it is recommended to push the variant building steps as far forward (i.e. late) along the value stream as possible, for example move it from production to assembly. On the supplier side, a close partnership is recommended with a few suppliers, instead of having a large number of competing companies. Non-value-adding activities, such as quality control should be done by the suppliers, regulated in a contract.

The book goes on to detail the Kanban system, including several examples, calculations, tables, etc.

<u>Factors covered</u>: All major criteria receive attention, the objectives as well.

<u>Relevance</u>: Very high, all subjects are covered, but hard to use as a planning process, not structured well. The focus on Kanban also excludes some cases, such as seldom used parts or C-parts.

4.8 Supplementary Methods

There are some very specialised methods in the literature that focus on one narrow topic. They cannot be used to plan the material flow, but can contribute some details. A few such ones are to be found below.

4.8.1 Method G – Inventory Optimisation

The thesis of Lars Fischer: *Bestandsoptimierung für das Supply Chain Management*[127] focuses on procurement methodologies for warehouses. The three main methods are:

- (s, q): if the inventory falls below *s*, a quantity of *q* is ordered *n* times to fill it up to *s*.
- (s, S): if the inventory falls below *s*, a quantity *S* - *s* is ordered to fill it up to *S*.
- (r, S): the inventory is filled up to *S* in regular intervals of *r*.
- (r,s,q): a mixed form, more flexible due to more parameters.

These are analysed in detail and evaluated.

<u>Relevance</u>: A good analysis in the one subject of warehouse supply.

[127] Fischer, 2008.

4.8.2 Method H – Selection of Control Method

The selection of a control method, according to a presentation by Till Potente: *Produktionsmanagement II - Vorlesung 5 - ERP III – Steuerungsstrategien*[128]

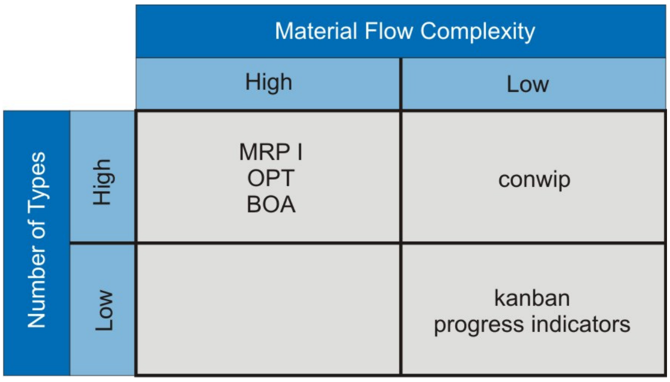

Figure 20: Field of application of production control methods.[129]

4.9 Evaluation and Summary

The above methods are hard to compare, as they are different in subject, scope, level of detail and other aspects. To enable an overview, the following table shows with green fields which of the topics are covered by which method. The topics marked with red are the main focus of this thesis, while the pink one is related to these.

Method	Suppliers	Purchasing	Inbound Ware-house & Picking	Transport	Material Handling & Supply	Control	Assembly Layout	Material Flow in Assembly	Sales & Outbound Log.
A - Traditional							X		
B - Linked Process Chain					X		X	X	
C		X	X	X	X	X	X	X	
D - VSM	X	X	X		X	X	X	X	
E - Lean + Innov. Methods		X	X		X	X	X		
F - Kanban	X	X	X	X	X	X	X	X	X
G - Inventory Optimisation		X							
F - Control Methods						X			

Table 3: Subject areas of the researched methods

[128] Potente, na., http://www.wzl.rwth-aachen.de/de/7ab8e31a4ca7f394c1256fb700481ac7/pmii-v05_ss09_ptt.pdf
[129] Source (translated): Potente, nY., p. 10.

The best coverage – not forgetting that coverage ≠ quality – is given by methods F, C and D, while E is also good, the others are narrowly focused. Pros and cons of the four best methods:

Method C – Material Supply According to Nyhuis et al.
This one has its strength in the classification of parts and purchasing strategies, as well as warehouse planning and tips for picking, these are the useful parts. The objectives of inventory reduction and therefore cost reduction are its weakness and the lead time is not taken into account at all, though it is a determining factor for flexibility and a high service level.

Method D – Value Stream Mapping
The strength here lies in the step-by-step instructions and practical structure, while it is light on important detail points. Usable as a rough structure, where the three main stages of application: demand, flow and levelling seem especially adequate.

Method E – Lean and Other Innovative Methods
As this wasn't one method, but several, there is no clear planning "path", just a mosaic of information. This can be used in specific details such as selecting a control method or in the management of C-parts.

Method F – Kanban
This last one seems to contain the most information, taking into account all the factors and showing the changes needed in assembly, logistics, company and personnel organisation. However, it isn't a convenient planning guide, the information is intermixed and no planning steps are given.

Conclusion
Not one of the planning methods found can serve as fully adequate material flow planning. Some are simply not planning tools and just give a stack of information, tips and tools without a structure (methods **E** and **F** as well as all the smaller supplementary methods). On the other hand, the others that are made as planning guides either come from the "wrong direction" (**A** and **B**), or leave out important factors (**C**) or simply do not have enough detail (**D**).

The conclusion drawn is that not one complete method for material flow and supply planning of assembly lines can be found in the literature. However, all the necessary information is available from different sources, one must select the best strategies and structure them together. It is therefore the objective of this thesis to synthesize an adequate, practical and usable planning methodology.

Chapter 5 – The New Method

We have concluded in the previous chapter that in order to meet the thesis requirements, a new planning methodology needs to be developed. The information needed for this can be drawn from different sources available. There are however a few issues that must be clarified and decided on before the development of such a model.

5.1 Goals and Restrictions

5.1.1 "Main Idea"

The methods researched come from different backgrounds and the new method needs a core idea as well. An important question here is: *Is logistics value-adding?* Most sources say no, as the customers aren't willing to pay an additional charge for it. A few sources point out extra services,[130] especially in outbound logistics that do add value, since they differentiate the product from the competitors, for which the customers are willing to pay more. However, for our discussion of the material flow inside the factory the assumption will be made that it is a non-value adding but necessary process. Since it generates costs and binds capital, the "main idea" of planning must be to **reduce the process structures to a minimum**. As they say, *simpler is better*. These minimal structures should never be damaging to the value adding processes, so the second criterion is a **maximal customer-orientation**.[131]

5.1.2 Economic Significance

The central goal of profit-oriented companies is usually to maximise the Return on Capital. The following diagram shows how logistics influences its different elements, whereby the main area of influence is the capital bound in inventory as part of the working capital.

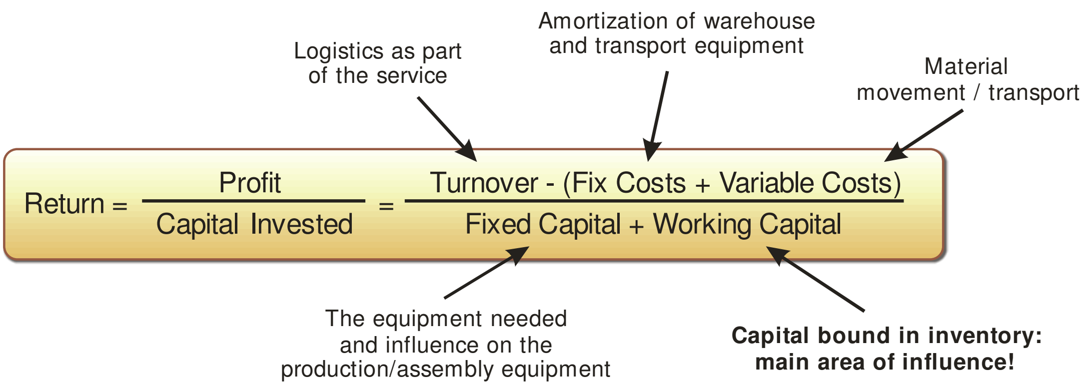

Figure 21: Influence of logistics on the elements of the *Return on Capital.*[132]

[130] Pfohl, 2004.
[131] For a list of sub-objectives that serve to achieve these two main goals, see Dickmann, 2007d, p. 112.
[132] Own diagram, based on Koether, 2001, pp. 1-2.

The important economic sub-goals of the material flow can be deduced from this:

1. Reduce fix costs ⇒ As little equipment and as small a warehouse as possible.
2. Reduce variable costs ⇒ Reduce material movement to a minimum, dispose of unnecessary steps.
3. Reduce fixed capital ⇒ As little equipment should be used as possible. Not only do complex automated assembly lines cost much, they are also much too inflexible.
4. Reduce working capital ⇒ Much capital is bound in the inventory, reduce it therefore (but not as much as to damage the processes), see also *Section 3.3*.
5. (Increase turnover ⇒ Increase customer satisfaction or offer extra services to increase sales or product price. Mostly a task of outbound logistics.)

5.1.3 A Lean Approach

As seen earlier, the existing methods contain all the detail necessary for our goal, just the proper structure is missing. From the different approaches, the best type should be selected to function as the base, on which all the details can be built up. Based on research as well as a few practical examples, the only approach covering all the objectives of cost reduction, lead time reduction, inventory reduction, a high level of flexibility and the all-encompassing customer-orientation seems to be a **modern lean model**. This Japanese method can be and has been successfully introduced first in Japan, then all over the world, leading to enormous benefits for the companies in question, their workers, customers and suppliers.

Lean is a comprehensive method, which affects all activities and departments of an enterprise, the material flow is also included. There are a large number of smaller tools and techniques that make up lean, the ones relevant to material flow planning have been discussed in detail in ***Chapter 2***. One of the most relevant ones seems to be value stream mapping or **value stream management** (VSM), as seen in *Section 4.5 – Method D*. The main ideas of this method will be used inside a lean framework for material flow planning.

It is however not the intention to use 100% lean or VSM over anything else, the decision for each part of the model is based on what seems to give the best results, this can lead to other techniques also appearing in the planning model.

5.1.4 Assumptions Concerning the Assembly Line

The subject area of material flow planning of assembly lines is too broad a topic for one planning method. One method cannot be adequate for all situations, unless it is either so vague as to be useless, or has so many “offshoots” and branches that it cannot be understood. The scope needs to be delimited, while still attempting to keep its area of application as broad as possible, in the following way:

The model will be developed for an assembly line with mostly manual assembly, or at most using a few simple machines, while avoiding extremes of the following parameters:

1. Company size: a rational minimum of at least a dozen workers. No upper limit is needed, although companies with thousands of workers per factory will clearly have specialists for planning and would need such a paper less.
2. Product size: not extremely small to require micro-assembly and not so large as to be unmoveable. The assembly of such large objects requires a different work organisation and would be a separate topic of discussion. The best case is an object that can be moved with hand by the workers, but is no requirement, as larger ones can be moved using mechanical tools, pneumatics, etc.
3. Components: special areas such as chemistry or microelectronics are avoided.

Manual assembly was chosen for its widespread use, but also because it meets the criteria of low costs (in this case, low investment) with high flexibility and small lot sizes, which are some of the main elements of modern and lean techniques; see lowest row in *Figure 22* below. Any other assumptions that may be needed will be made at the appropriate step.

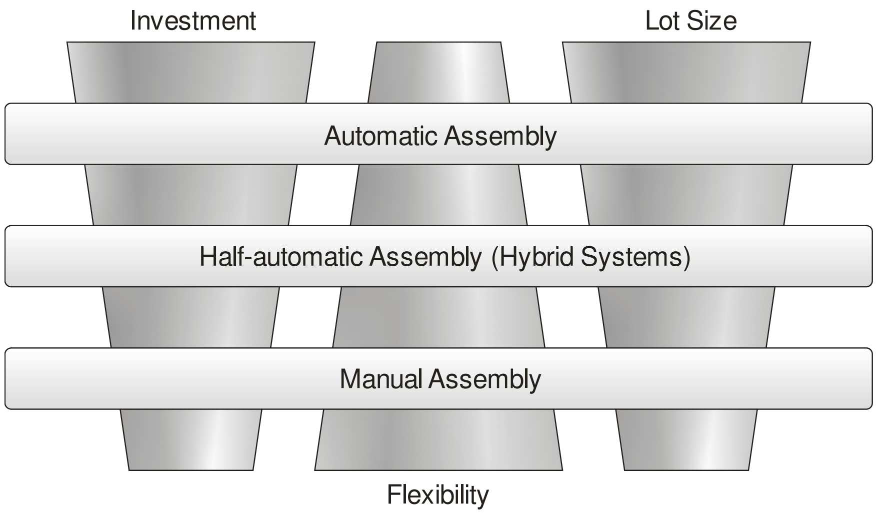

Figure 22: Selection criteria for the assembly system.[133]

5.1.5 Definition of Scope

Relation to Assembly Line Planning

The relationship to assembly line planning must also be decided. The weakness of some of the researched methods was a sequential development of the assembly line first and then the material supply, so that the material flow criteria didn't influence assembly line planning. This is not too fortunate since the two belong together, as a functioning whole. The lean approach that was decided on itself requires that the line and the material flow "evolve" together.

[133] Source (translated): Lotter, 2006, p. 3.

Along these lines, it is presumed that the assembly planning takes place alongside material flow planning. While this thesis discusses material flow planning, the appropriate steps of the parallel assembly line (re)design will be referred to. The relationship of the steps to greenfield planning (completely new assembly line) and brownfield planning (redesign of existing line) will also be considered.

Boundaries of Material Flow

This thesis focuses on the material flow inside the factory, starting from the inbound warehouse till the finished goods stock, with special emphasis on the parts supply **to** the line. Inbound and outbound logistics and transportation planning are outside of scope.

5.1.6 Thoughts on the Structure

The foundation of the basic structure of the planning method is the five steps of a lean process. First the **value** is defined, that is: what constitutes value for our customers, what do they want to buy? For this, a **value stream** must be identified, which is a group of processes, along which value flows from the suppliers through production and assembly to the customers. As high a level of **flow** should be implemented as possible, while all steps should only produce if the customers **pull** them. The steps of flow and pull are especially vital for this thesis. Finally, the new system is never really "finished", instead, a constant redesign should make it ever more efficient and productive and require ever less personal and other resources, i.e. a road toward "**perfection**."

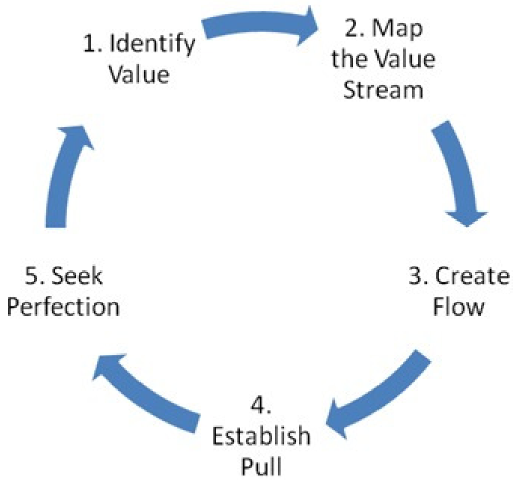

Figure 23: Five steps of Lean.[134]

The creation of a current state and a future state value stream map, as in Method D – Value Stream Management: expands this structure. The future state planning also includes the three main steps of **Demand**, **Flow** and **Levelling**, whereby the last one falls in the separate assembly line planning. Finally, the whole method is expanded with other needed details, including an information gathering first step, details on Kanban and other specific areas.

[134] Source: http://www.lean.org (accessed on 08.08.2009).

To help give an overview, a synopsis of the method is given in the next section. Then the steps are discussed in more detail, with each step being summarised at the section's end with a flowchart. Steps that are outside the scope of the thesis are also shown as the "side branches" in the right column in the flowcharts and are not explained in detail.

5.2 Method Overview

The planning method starts with the steps needed if the material flow planning runs parallel with a redesign of the assembly line. It is possible that some of the first steps have already been carried out or are given, in this case one can start at a later step, as late as Step 5.

The first step, or more of a *"step zero"* are all **preparation activities**, such as holding the project kick-off, since the planning is assumed to be carried out as a project, using tools of project management. Customary steps here are forming a cross-functional planning team with a responsible leader, holding regular meetings and in case of a lean approach, training the employees in lean tools and principles.

Lean and other modern manufacturing systems focus on the customers and his needs, and therefore on the products that can meet these needs, i.e. the "*value*" created by the company. Before the actual planning steps, if it has not been done before, it is advised to restructure the organisation itself according to product families.

Following any needed preparations, in **Phase 1** information gathering is carried out. The collected data will support all the decisions that are made later on. It is important therefore to carry this step out properly and obtain correct data. The data collected can be stored in a so-called *Plan for Every Part* (PFEP) database.

Phase 2 entails mapping the current material flow(s), analysing these and finding any wastes that are present. A valuable tool in this phase is *Value Stream Mapping* (VSM) with which a compact visual summary of the current state of material flows, information flows, the assembly processes and the most important system data can be created. The processes are then detailed and wastes are sought. This step naturally does not apply to greenfield planning.

Phase 3 focuses on the demand and the capacity. If a completely new assembly line is planned (*greenfield*), one can skip the previous phase and continue Phase 1 with Phase 3. The foreseeable customer demand is calculated – for which there are a number of measurement and forecast methods – which give the primary demand on products. This is then translated into secondary and tertiary demand. The primary demand is determining for planning the assembly line and the material flow *inside the line* – that is the flow of WIPs. The secondary and tertiary demands are required later, for the supply of parts and material *to the line,* planned in Phase 6.

From the demand the takt time is calculated as well as the pitch, if needed. At this stage, assembly line planning requires calculating the capacities of the processes, finding any bottlenecks or constraints and resolving these. For material flow planning any required safety inventory, buffer inventory and finished goods supermarket on the outbound side are calculated.

A general, high level planning of the whole new assembly line can now take place. A division of this stage into only material flow planning or only assembly planning is hard, the two are intertwined here. **Phase 4** therefore needs to reach beyond the narrower thesis scope and look at the creation of flow inside the assembly line. Continuous flow is the goal, if this is not possible then flow, if this is not possible then partly flow, partly pull and finally if all else fails a fully pull system should be implemented, while push should be avoided. The results of the assembly line planning are mapped on a future-state VSM. Detailed planning, line balancing and operator job organisation are also planned at this stage, these are however not part of this thesis.

Phase 5 is built on the results of the assembly line planning carried out previously. In case the whole assembly line is given (non-alterable), one can skip phases 2, 3 and 4 and continue here. In this fifth phase, the separate parts of the assembly line are connected with each other, with the inbound and outbound warehouses and – if there is such inside the factory – with production. The supply of each process with WIPs is decided on, which also determines how the upstream process is controlled. Possibilities here are continuous flow, FIFO lanes (*flow*), a Kanban system (*pull*), in-process supermarkets (*pull*), computer-assisted scheduling (MRP, *push*) or variations on these.

After Phase 5 the required details of assembly are worked out – such as production levelling or cell design – and entered on the value stream map, these are not part of our planning method.

Once the material flow inside the assembly line is planned, the *supply to the line* with the purchased parts and materials can be planned in **Phase 6**. This step is divided into several sub-steps and follows the method of Harris and Harris:[135]

- **6.1** A central purchased-parts market is built. The minimum and maximum inventories to hold (defined per part), the required space, rules of operation, etc. are determined.
- **6.2** Delivery routes are designed. Goal is to deliver materials "to the operators' fingertips." The delivery aisles and routes, the transportation method, the delivery points and the physical parameters of the delivery points (size, construction, etc.) are planned.

[135] Harris and Harris, 2009.

6.3 Pull signals are implemented to pull the required parts at the proper location. FIFO lanes, kanban loops or supermarkets can be used. The precise parameters are calculated, for example the number of kanban cards per loop.

6.4 The system is continually improved: wastes are eliminated, such as excess storage space, inventory, etc. Continuous monitoring is recommended as well as deciding on key performance metrics.

With these steps, the material flow starting from the customer demand, upwards along the value stream until the inbound warehouse (= purchased parts market) has been planned. **Phase 7** would then be planning the inbound logistics: the part of the value stream between the company and its suppliers. This falls outside the range of the thesis and is only referred to.

Finally, the **implementation** itself needs to be planned and then carried out. This requires project management, change management and some lean tools and comprises a separate topic. Many authors recommend implementing one cell first, and then scaling it up to the entire factory. Part of the lean philosophy is continuous improvement, usually comprised of two methods: small changes in the form of *kaizen* workshops, and large-scale, radical changes (*kaikaku*), these can be used on the long journey towards "*perfection*."

On the following page is a compact and simplified flowchart of the planning process presented here. It tries to give an overview, as well as show some of the most important activities that run parallel with the material flow planning but are outside the scope of this thesis. The three central columns marked with thicker borders show the planning methodology, with the ***"Main Steps"*** column showing the major tasks and the ***"Substeps"*** containing more detail. Please note that the ***"Inputs/Outputs"*** also contains the outcomes of the separate assembly planning processes, as these are often connection points with the thesis subject. The last column on the right contains some of the main tasks that should happen parallel to material flow planning, with the arrows showing the interrelations. Some possibilities for starting steps are also shown on the left. The following sections will then detail all the phases of the planning project. At the end of each section a more in depth flowchart of the activities is given, using the same layout as the overview chart.

« A "Key Results" icon points out the main results of each phase.

A Note on Sequentiality

Finally, a note on phase sequence: the planning method was developed and is described based on sequential phases as in 'traditional' project management. Steps that do not need the outputs of the previous steps can however be done parallel with previous activities. This compresses the timeline but widens the number of simultaneous planning activities and is in accordance with modern methods of simultaneous or concurrent engineering. One example is demand analysis (phase 3) which can be done parallel with the current state value stream analysis (phase 2).

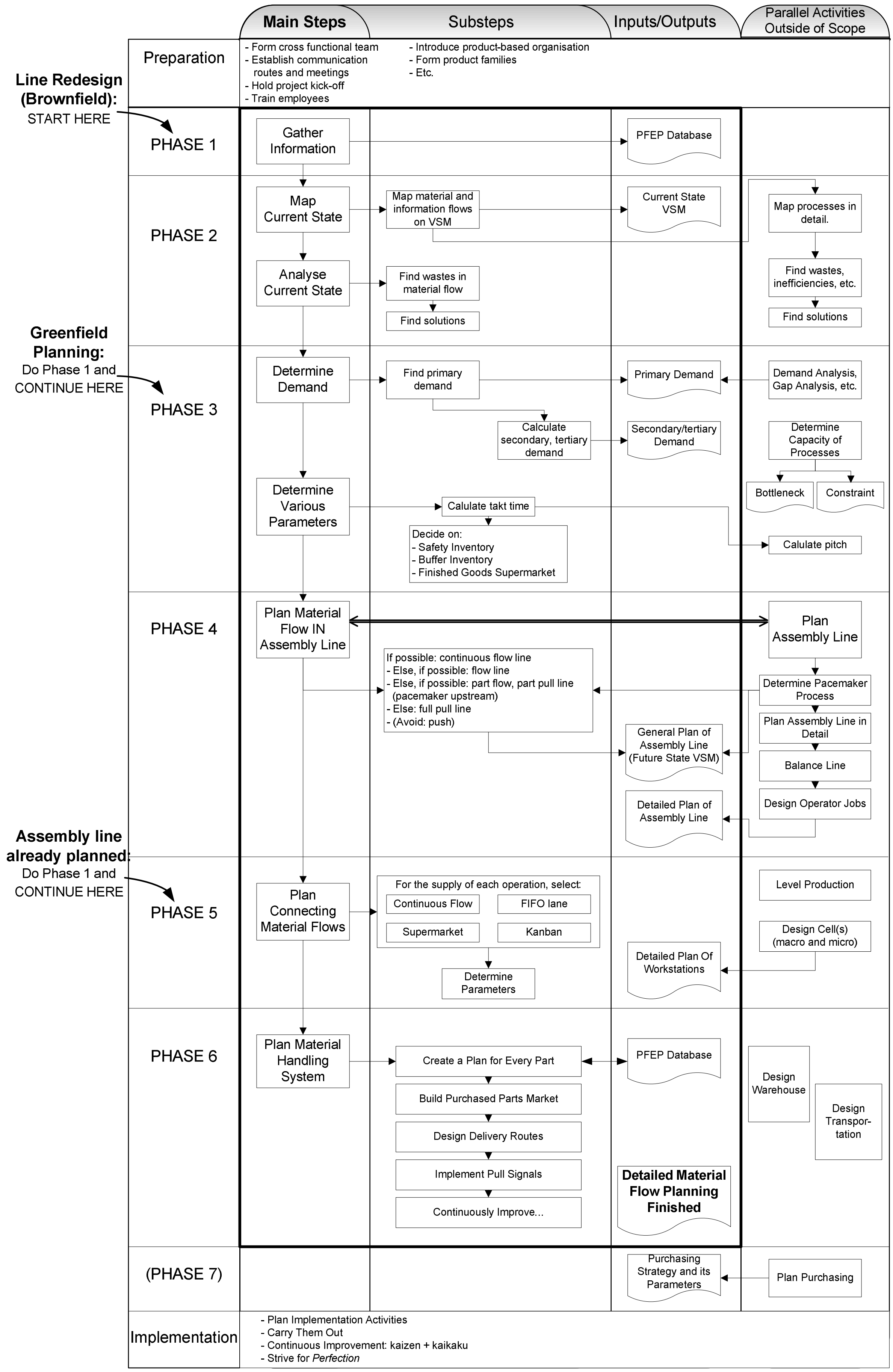

Figure 24: Overview Flowchart.

5.3 Preparation Phase

All grounding activities that need to be carried out before planning can start are summed up in the **preparation phase**.

5.3.1 Project

This is not an operative part of the thesis but must be mentioned shortly as it is an important “zeroth” step. It is assumed that planning the material flow will be carried out as a project. In this case, the basic practice of project management can be observed. The steps to take are proposed by Carl Wright in his twenty step lean implementation in the following way:

1. *“Form team (mix of lean manufacturing and relevant business experience)*
2. *Develop communication and feedback channel for everyone*
3. *Meet with everyone and explain the initiative*
4. *Begin to train all employees (lean overview, 8 wastes, standard operations, kaizen, RCPS, PDCA)”* [136]

Note that some of these are ongoing activities that continue through the project, such as training the employees. *Section 2.3 - Starting a Lean Project* has discussed this step in more detail.

5.3.2 Organisation

If the company in question wants a full-blown introduction of lean instead of just a new assembly line, a larger reorganisation of the business might be needed. Many authors recommend structuring the organisation according to products or product families (“*segmentation*”). This enables the *flow of value* across the enterprise, without the invisible walls at departmental boundaries. Creating such a product-oriented organisational form is also part of the preparation phase, though it is a longer, ongoing process. See *Section 2.4*.

If it has not been done before, the division of all the products into families should also be carried out. A simple approach is building a process profile of all the products, and grouping similar ones together, see *Section 2.4.3*.

KEY RESULTS

This phase should provide the organisational requirements and project base for successful planning and implementation.

[136] Wright, 2007.

5.4 PHASE 1 – Gather Information

Assuming the preparatory activities were carried out, we now have the products that our customers need (i.e. we have defined the value) grouped into families, as well as product teams that are responsible for each family from start to finish, from the warehouse to the finished goods store. The real planning can start now with the first major phase: information gathering.

At the start of planning, a number of input data need to be collected to help in future decisions. This is the all important base upon which the rest of the development rests, so time and resources should not be spared here. Going to the shop floor and watching the activities there helps not only to collect data, but to observe problems and find rooms for improvement first hand, as well as to break social barriers and enable communication with the workers. They are the ones producing or assembling and they can be the source of many good ideas.

The information needed includes all the basic factors from chapter 3, but much more detail is needed. It is not only a good idea but almost a prerequisite for a lean material flow design to make a complete Plan for Every Part (PFEP).

5.4.1 Have a *Plan for Every Part*

The Plan for Every Part (PFEP) means that each and every part that is used in production or assembly, including mechanical, electrical components, coverings, tubes, wires, clamps, from the smallest screw to the biggest product covering panels are all registered and their data recorded: how and from whom it is purchased, how it is stored, where and how often it is used, etc. This serves as a base, whose data will be used in the next steps of planning. The PFEP itself is a worksheet or database with a number of data entries for every part. Although there are complex and costly programs such as ERP systems that allow for the entry of the needed data, a simple database (e.g. Access) or even an Excel worksheet will do.

The following table is an example of the types of information that are stored in a PFEP database for each component, arranged here in a few logical groups.

Identifying Characteristics of Part

ID	A running number from 1 to n, internal use in database
Category	Component category
Part Number	A unique part number
Part Description	Short and long description
Component Type	E.g. metal part, plastic part, cable, LED, capacitance, etc.
Usage Location	Process/area where it is used, e.g. *Cell 7*
Storage Location	Location in warehouse

Purchase and Vendor Information

Buyer	Code/Name of employee responsible for the purchase
Prime Vendor	Code/Name/Location
Standard Cost	Cost of 1 part
ADU	Average Daily Use (calculated from e.g.: past 6 months)
STD of ADU	Standard Deviation of ADU
Order Frequency	How often it is ordered, in [Days]
Order Lead Time	Time from order to availability for assembly (= handling time at supplier + transit time + handling time in own factory)
Transit Time	Time from shipment to arrival
Minimum Order Quantity	Minimal number of units that can be ordered

Inventory Information

Buffer Inventory	Inventory level that should always be available
Pull Trigger Point (PTP)	When to order, in [pieces] and in [days on hand]
Average Inventory	In pieces
Current Stock	In pieces and in days on hand
Current Cost	Cost of current stock
Average Cost	Cost of average stock
Days to Reach PTP	Average days remaining to reach PTP

Material Flow Information

Maximum Hourly Usage	In pieces, based on the most often assembled product that contains this component
Kanban Quantity	Quantity in kanban loops

Physical Information

Kanban Dimensions:	Width, Length and Height of Kanban container
Supply Outer Dimensions	W, L, H
Supply Inner Dimensions	W, L, H
Part Weight	Weight of 1 unit of material
Container Weight	Weight of 1 container of parts

Table 4: Common Entries in a PFEP.[137]

[137] Based on an existing lean production company that will remain anonymous, as well as Harris, n.Y. pp. 2-3.

Some of the entries are primary collected data. Other entries can be calculated from these via formulas. These are just examples, there can be other entries, depending on the situation and what is dictated by common sense.

The central idea is to have everything available in one central database, and not scattered about the company in different departments. A general way to create a PFEP is described by Harris:[138]

1. First the application is selected, for example an Excel worksheet, or an Access database, taking into consideration that the database should be available and usable by all employees.
2. Then the data is entered, in as small chunks as possible, e.g. width, length and height in separate fields, to enable calculations. Note that most of the information already exists in the company but is “invisible” because it is scattered in different places, under the control of different departments.
3. For smaller companies it can be filled with all parts in one go, for larger ones it can be filled up product-by-product or cell-by-cell. Completeness of the data is very important, nothing should be left out, so don’t rush and try to do everything at once but start small and then expand.
4. Keep an eye on the future and make sure all new products are completely PFEP documented. It is useful to make a “desired” field for the values that should be changed in the future. For example, the Minimum Order Quantity might be 500 pieces, but the desired amount is smaller, for example it would be better to be able to order less pieces, e.g. 100.
5. Maintain the integrity of data, this includes putting someone in charge of the database (*PFEP manager*) as well as laying the guidelines for changing entries. A standard *change request form* is good practice.

Once it is established, the data can be used for different stages in planning, from high-level decisions like purchase strategies to detailed planning, like the size of racks in the warehouse.

KEY RESULTS

By the end of the phase a plan for every part database should exist and contain all products with current information.

[138] Harris, 2004, pp. 3-5.

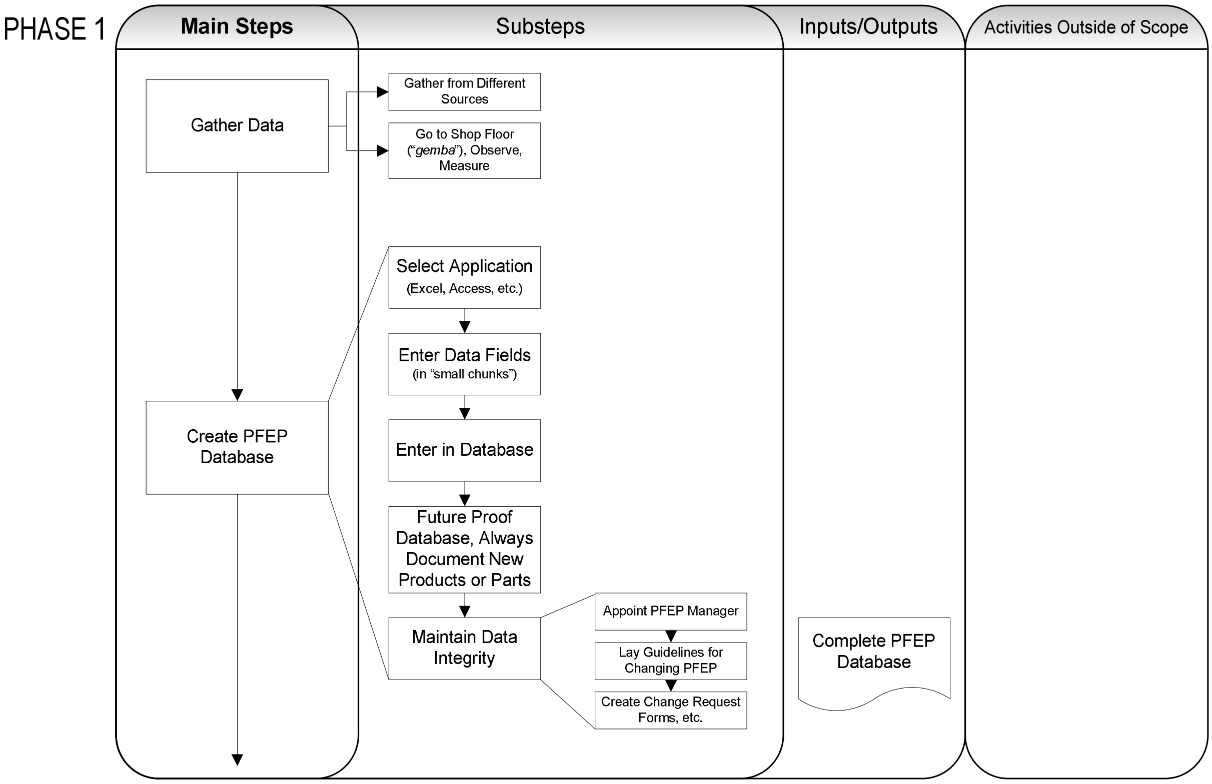

Figure 25: Phase 1 Flowchart.

5.5 PHASE 2 – Map and Analyse the Current State

It is usually not recommended to redesign the whole assembly operations of an enterprise all at once, especially if it is new to lean. One value stream should be selected first, one that is important, for example because it has a high production volume or because it is performing badly and therefore needs a redesign. See *Section 2.5.1* for possible selection methods.

5.5.1 Map the Current State

Before doing any work on the future design of the assembly operations, the current state should be analysed to help see the areas where improvement can be made. This is only valid for redesigned assembly lines, i.e. brownfield planning. Skip this phase for greenfield planning or if the new assembly line has already been designed.

1 – Map Assembly Process using VSM

Value Stream Mapping will be used in this step as it has several benefits, see *Section 2.5.2*. First, the current state of production and assembly is mapped on a so called *Current State Map*. This presents a birds-eye-view of the whole value stream, showing material flows, information flows, processes and process data as well as other important, high-level information. The mapping process is made up of the following major steps:

- Gather the needed information, using a *VSM Information Gathering Checklist*, see an example in *Section 2.5.2*.
- Draw the current state map, using the method in the aforementioned section and enter the data.
- Calculate the *Total Cycle Time (= Sum of process cycle times)* and the *Lead Time (= sum of all WIP Days on Hand).*

The resulting VSM is invaluable both for the assembly planning and the value stream planning – as an overview, see the example below:

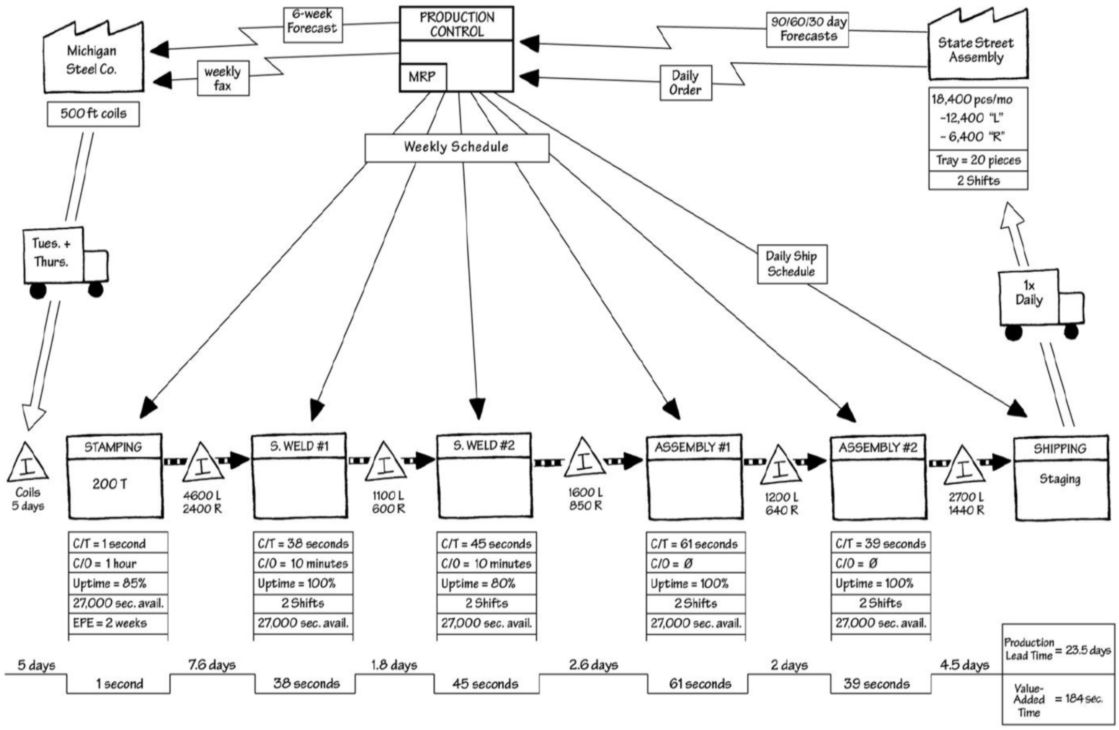

Figure 26: Example value stream map of a manufacturing line.[139]

2 – Map Assembly Process in Detail

To take details into consideration, the whole assembly process should be mapped, with tools such as *Process Mapping* (also called *Process Charting* or *Flow Charting*), which depict the sequence of events to build a product. When selecting the method, a distinction between value-adding and non-value-adding steps should be possible. For further discussion, see the literature.[140]

[139] Source: Womack, 2009, p. 35.
[140] For an example method, see: How To Map A Process – Six Steps To Success http://www.strategosinc.com/mppng1.htm

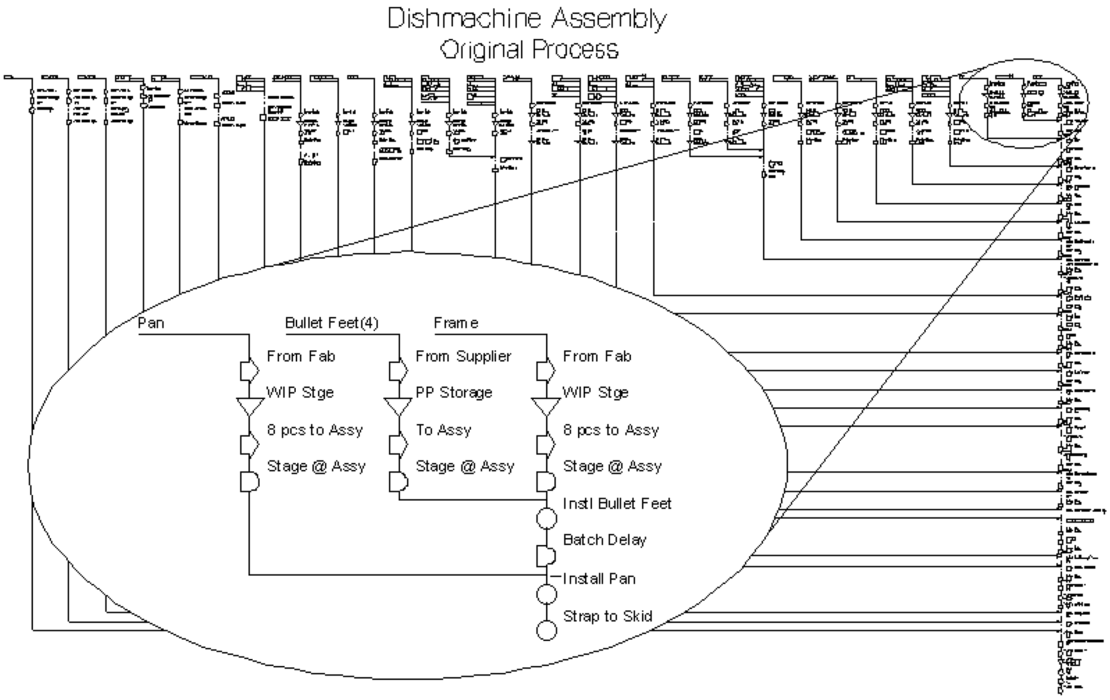

Figure 27: Detailed process map of the assembly of a dishwasher.[141]
The main assembly line is the right hand column,
while the subassemblies are the branches that come in from the to the left.

3 – Evaluate the Current State

Now that there is a picture of the current state of assembly, it needs to be analysed, evaluated and possibilities for improvement found. The handling of waste is made up of three major steps:

1. Find wastes. For the material flow, the following types of waste are the most important: unnecessary movement of material, waiting and inventory.
2. Categorise the wastes into: non value-adding but necessary operations (type one muda) and non value-adding and unnecessary operations (type two muda).
3. Eliminate the wastes. This is naturally one of the goals of the rest of the planning method itself but already at this stage the person or team doing the planning can think about possible solutions. Type two wastes can be eliminated in the short run, while type one can only be resolved in the long run.

These are mostly intuitive processes for which making a detailed sequence of activities seems to make little sense. There are however a few concrete tools that can be used. One is the *spaghetti diagram*, which makes the physical material flows apparent:

[141] Source: Strategos Inc.: Example- Mapping an Assembly Process, http://www.strategosinc.com/mpping4.htm (accessed on: 19.08.2009) .

- Draw the current layout on a board, or using any other method.
- Draw the paths of all products, each one with a different colour, also differentiate material flows from information flows. The origin of its name is then easily seen: the material flows of a traditional factory will look like a plate of spaghetti.
- Analyse routes, rearrange equipment as necessary; these can lead to quick and substantial improvements in the material flow even before a large scale lean transformation can be made.

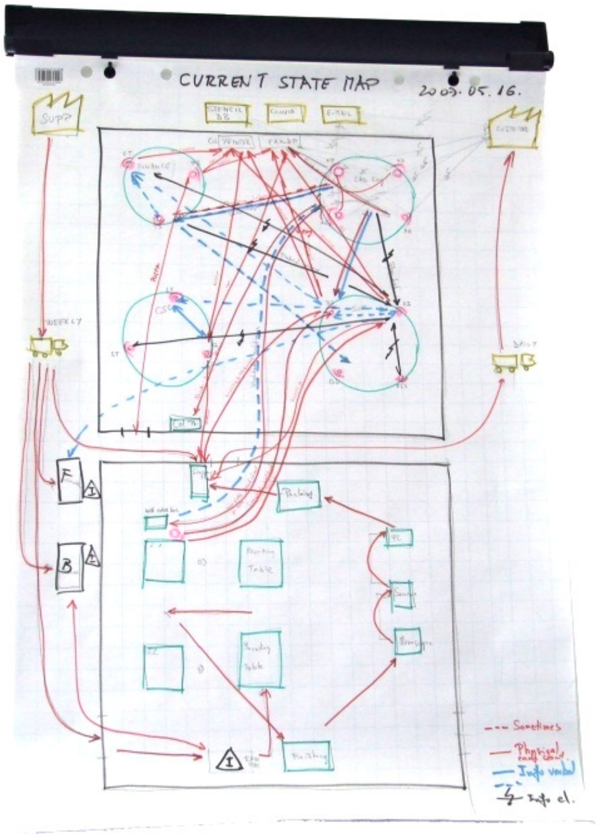

Figure 28: Spaghetti diagram.[142]

At the end of the phase, a current state value stream map should be available with identified wastes. Thought can go into possible solutions, though these can also be resolved during the next phases.

[142] Source: a manufacturing company (anonymous).

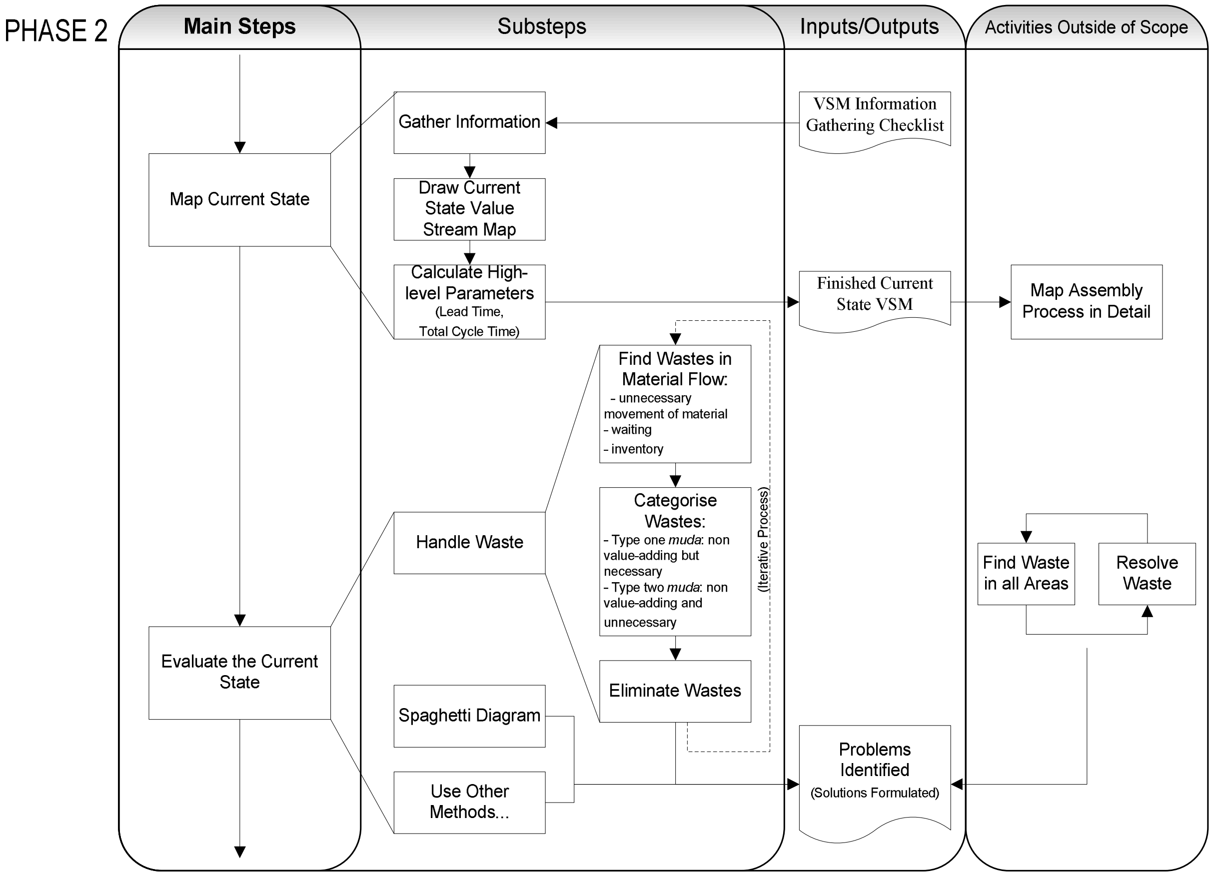

Figure 29: Phase 2 Flowchart.
Note how finding and elminating waste is an ongoing, iterative process that does not stop at the end of the phase.

5.6 PHASE 3 – Demand and Capacity

Having an understanding of the current situation of assembly operations, the future state can now be planned. The data gathered and the wastes uncovered will be of much help in these phases. Starting from the current Phase 3 until the completion of the assembly line plan at the end of Phase 5, all decisions that show up on a Value Stream Map should be added to a Future State VSM. This is self-explanatory and will not be mentioned at every step.

In the demand phase of planning, the customer needs are surveyed as accurately as possible and the most important characteristics of the new(ly redesigned) assembly line are derived from this. The capacity of company processes is also determined in this phase, but this is not part of our planning method.

5.6.1 Analyse Demand

Note: This step, while in this method described sequentially after phase two, can also be started earlier and done parallel with phase two.

The various types of demand from the production and assembly perspective have been discussed in *Section 3.2.1*. A **demand analysis** needs to be carried out to find the following demand types from a management perspective:[143] **actual demand**, based on sales data of the current and previous years; **future demand**, which is an forecast based on the actual demand; the **potential demand**, which is an estimate of the maximum sales volume under ideal conditions and finally the **evolution of demand**, whereby market trends and phases of the product lifecycle are considered.

The results show the primary demand, that is, the demand on final products. For one, the primary demand is needed for planning the assembly line and for the thesis more importantly the material flow inside the company and is used in **Phases 3**, **4** and **5**.

The secondary and tertiary demands are calculated from the primary demand, using the information contained in the *Bill of Materials* (BOM) of all products. These two demand types will be needed for the *Material Supply to the Assembly Line* (**Phase 6**) and for the *Purchasing Strategies* (**Phase 7**).

5.6.2 Determine Takt Time

The takt time, that is the speed sales (see *Section 2.5.5*), is calculated, whereby the goal is to set the *cycle time = takt*.

$$takt\ time = \frac{available\ operating\ time}{production\ requirement\ (= demand)} = [time\ per\ piece]$$

The so called *50-second rule* should be observed, see *Section 2.5.5*: if the takt time is significantly lower than about 50 seconds, then a second assembly line should be seriously considered.

5.6.3 Other Parallel Activities

At this phase, the following activities should also be carried out. These are not part of material flow planning, but are too important to overlook, and need to be touched on:

Determine Pitch

$$pitch = takt\ time \cdot pack\ out\ quantity = [s]$$

The pack out quantity can be dictated by the containers that are shipped, or any other larger unit that seems logical for production levelling / heijunka.

[143] N.N.: Writing a Business Plan - Part 3 - Market Analysis, Demand Analysis.

Determine Own Capacity

Calculate the current ability to meet demand, using the information gathered during the value stream current state mapping and if needed going to the shop floor once more. To calculate the capacity, the operations closest to the required takt time as well as the processes with the lowest uptimes should be considered.

$$Capacity = \frac{Available\ production\ time}{Current\ cycle\ time} \cdot Uptime[\%] = [pieces]$$

Find Bottleneck(s) and Constraint(s) (see *Section 2.5.8*)

- If *bottleneck capacity* > *demand*, then it is less of a problem.
- If *bottleneck capacity* ≈ *demand*, then the goal is to constantly feed the bottleneck with material as any unused time reduces the whole system output. One solution is having a buffer stock before the operation. Try to eliminate such bottlenecks.
- If *bottleneck capacity* < *demand*, then it must be resolved, otherwise the assembly will not be able to meet the demand.

5.6.4 Determine Stock at Shipping

As already mentioned, modern planning methods such as lean start downstream at the customers and plan step-by-step upstream up to the suppliers. Having the demand, the next step is setting the stock at shipping – the outbound part of the factory. While a complete lean implementation might enable complete production-to-order without outbound stock, such a condition might take months or years to reach but customers demand needs to be met in the meantime. This will probably necessitate the implementation of one or more of the following: a buffer inventory, a safety inventory and a finished-goods supermarket (see *Section 2.5.9*).

1. Determine if a **buffer inventory** is needed. The larger the variations in customer orders, the more it is needed.
2. Determine if a **safety inventory** is needed. The larger the variations in internal processes, the more it is needed. Tools such as six sigma can lower the variability of processes and reduce the need for such a solution.
3. Determine if a **Finished-goods Supermarket** is needed. This is the case if the production processes cannot guarantee a continuous flow of products, a very high service level is required or the lead time is longer than what the customers are willing to wait.

Calculating Buffer and Safety Inventories

To calculate the size of these, data on the reliability of the value stream from previous time periods and the experience of those most close to the operations are needed. Statistical methods can also be used, with the inputs of average demand, standard deviation of demand and the α-value (essentially: in what % of cases do we need to meet the fluctuating customer demands).

Demand will be more than the average with *StdDev*Z(1-α)* pieces in *1-α* percent of the cases, therefore to cover this extra demand:

$$buffer\ inventory = standard\ deviation(demand)\ \cdot Z\ value$$

and analogously for production/assembly deviations:

$$safety\ inventory = standard\ deviation(production\ \&\ assembly)\ \cdot Z\ value$$

Here the standard deviation must be calculated for the length of the replenishment time. In this case this is the lead time. If this value is only available for another time interval *'t1'*, it can be adjusted so:

$$StdDev_{replenishment\ time} = StdDev_{t1} \cdot \sqrt{\frac{replenishment\ time}{t1}}$$

The data available in the PFEP database is often the standard deviation of the average daily use (ADU). Therefore, multiply this value with the square root of the number of days of replenishment time.

The Z value is a function of 1-α of the inverse normal distribution, whereby $1 - \alpha = Service\ Level$. To calculate in Excel for example:

$$Z = NORMINV(1 - \alpha, \mu, \sigma) = NORMINV(1 - \alpha, 0{,}1)$$

Please refer to the literature for more detailed calculations.[144]

[144] See for example: A Comparison and Evaluation of Two Distinct Inventory Buffer Sizing Methods: The Functional Method and the Deterministic Processing Time Model, http://ocw.mit.edu/NR/rdonlyres/Mechanical-Engineering/2-852Spring2004/FAE6803E-42B6-41D2-ACEC-CF22F8D40437/0/inven_sys_paper.pdf (accessed on: 02.09.2009).

Determining Finished-goods Supermarket

The company's products should be classified into two groups based on past and projected demand data: supermarket parts and non-supermarket parts:

- All products that have small and erratic demand, i.e. are only ordered at irregular intervals in low quantities, a supermarket stock for these is not needed, they will be made to order.
- All products that have a more constant and high demand are supermarket parts.
- There is usually no set level for a finished-goods supermarket since its job is to smooth demand into production, it will fluctuate. It is however good to have an upper control limit (too much stock => reduce production) and a lower control limit (too little stock => review sales rate, maybe increase production rate) similar to statistical process control.[145]

If any of these three solutions is needed, draw it on the future state map. These solutions to problems are not lean themselves, since they mean extra inventories. They do however provide a way to meet customer demand even if problems arise. The goal is to work towards reducing and eliminating them.

KEY RESULTS

The key results at the end of the phase are data on the current and thoughts about the possible future demand. Demand on parts (2^{nd} and 3^{rd} demand level) is available. Takt time and the stocks of finished goods have been determined.

[145] Kerber, 2004, p. 16.

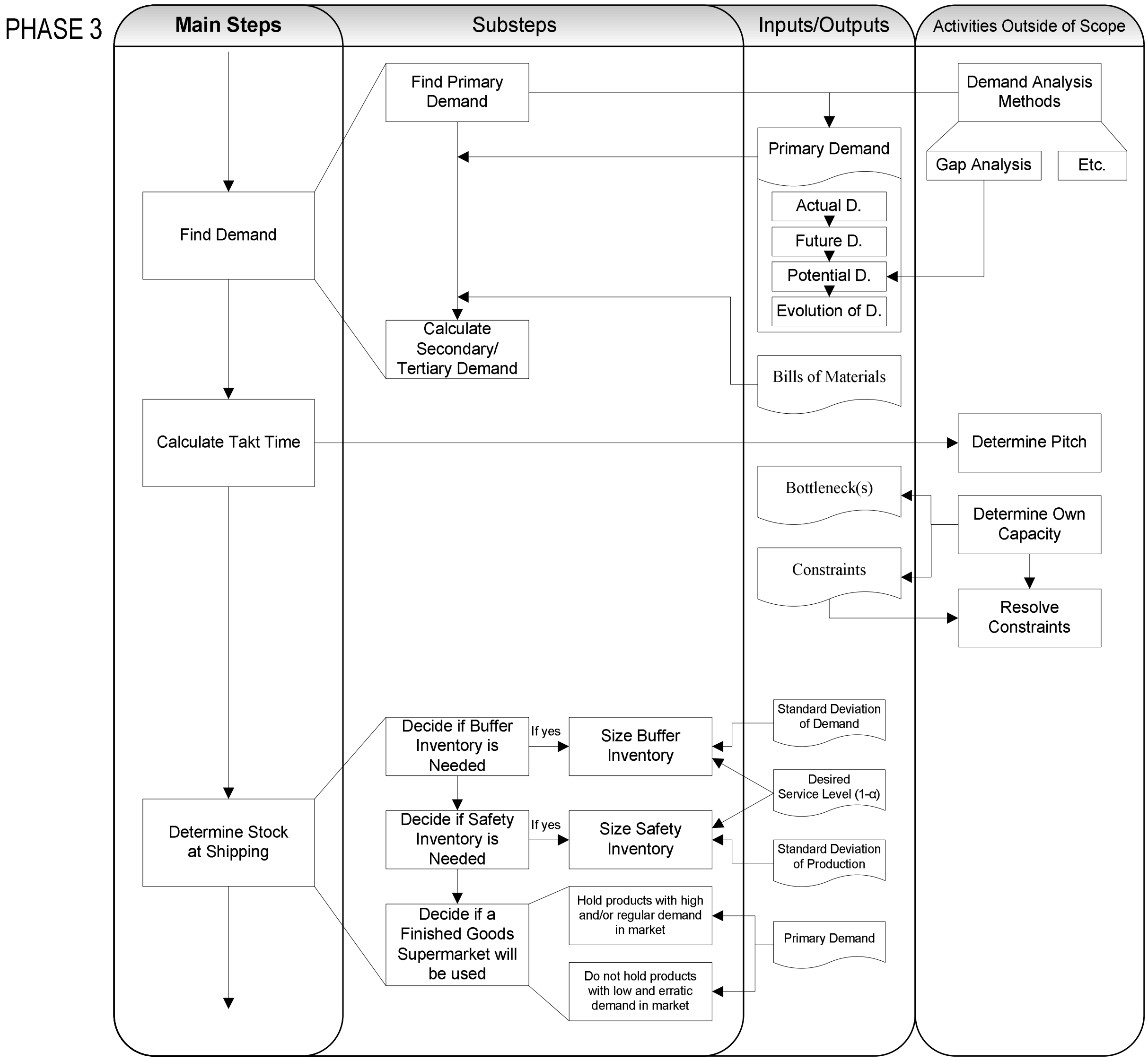

Figure 30: Phase 3 Flowchart.

5.7 PHASE 4 – Material Flow in Assembly Line

We have now reached the most important planning phase, where the future state must be designed, using all the information gathered, eliminating the uncovered waste, implementing a cellular design if possible and meeting all the ***Chapter 3*** requirements. Dividing this phase into a separate material flow planning part and an assembly line planning part presents impedimental problems. They seem so intertwined that it is not really possible to separate the two aspects, especially since the planning of a lean assembly line in this phase is material flow oriented. These characteristics have led to the conclusion to present this phase with both material flow and assembly aspects.

As all companies are different, the specific steps in this planning stage will be different. One must always keep the local circumstances in mind during the project and not just implement a mixture of tools from the lean toolbox.

5.7.1 Decide on Level of Flow

Continuous flow (aka. *single piece flow* or *one piece flow*) is most often described in the literature as being the ideal manufacturing system. It has a number of benefits and leads to extreme reduction of work in progress inventory, lead time, quality errors and other wastes, while maximising all of our Chapter 3 objectives. This means that the objective in Phase 4 is to reach this ideal state. Depending on how well the assembly line can meet the requirements of the different levels of flow, only a lower level of flow might be possible, see *Section 2.6*. Through improvements to the system and suitable assembly line planning, as high a level as possible should be striven for. The steps to take:

1. Compare the requirements of **continuous flow** (*Section 2.6.1*) with the current assembly line. Decide whether the requirements can be met. Try to implement lean tools and techniques to make this possible.

> Viewing an example company (based on the assumptions of *Section 5.1.4*), the following emerges: a mainly handwork assembly does not contain operations where a batch size > 1 would be needed, as there are no large machines. Besides this, the operation times of the workstations can be more flexibly divided uniformly so that each is under the takt time. This presents no hurdles to continuous flow. What does, however, is the stability of the process. This needs to be decided based on the given situation but it can be assumed that a company just starting on the path to leanness cannot sustain a pure continuous flow. A "less ideal" value stream must be planned, while continuous flow remains as the long term goal.

2. If continuous flow is not possible, try to implement **flow**, observing the requirements of *Section 2.6.2*. As before, try to make this possible with lean tools.
3. If full flow is not possible, try to implement a **part flow, part pull** system, observing the requirements of *Section 2.6.3*.
    a. Place the Pacemaker as far upstream as possible. The part of the value stream before the pacemaker will be pull, the following processes will flow. Observe the requirements on pacemaker:
        - No downtime
        - No changeover or very little (< 1 min)
        - Greatest worker flexibility

> These requirements are usually satisfied by the assembly processes, so the pacemaker is often somewhere in assembly.

4. If only the very last operation can be the pacemaker, then this is a **full pull** system.
5. If for some reason a pull system cannot be created, then the only alternative remaining would be traditional **push**. As this is to be avoided, implement lean tools and redesign the line, the process, the product or anything else to make one of the first four alternatives possible.
6. **Iterate**: in time, evolve from pull to flow and then to continuous flow.

These steps are actually part of a complex, intuitive process that the project team must go through to reach a feasible future state design. This iterative process is shown at the top of the Phase 4 flowchart in *Figure 31*.

5.7.2 Other Steps in Assembly Line Planning

Once the decision for the line type – based on the level of material flow – the rest of the line is planned. As this falls outside the thesis scope, just a very short list of activities will be given, also seen in the right coloumn of the phase 4 flowchart below.

1. Richards provides a simplified guide to carrying out the first line planning activities:

   - *"Form cells based on takt time*
   - *Define standard work content for each operation to be < takt time*
   - *Separate worker from machine (jidoka)*
   - *Develop quick setups & standard WIP (SMED)*
   - *Standardize operations"*[146]

2. The assembly cells, as well as any separate operations that cannot be built into flow-based cells are added to the future-state VSM. Also add relevant data and the number of operators per cell.

3. Plan the cells in detail, for a short overview, see *Section 2.6.6*.

4. Balance the line. Tools to help enable line balance:
   - Standardised work: for consistent flow and high productivity, this basically means using an agreed upon "best practice" as work instructions for the given task.
   - Quick changeover or SMED: for pushing too high cycle times down under the takt time.
   - Autonomous Maintenance and other methods.

5. Design operator jobs.

[146] Richards, 1999, p. 9.

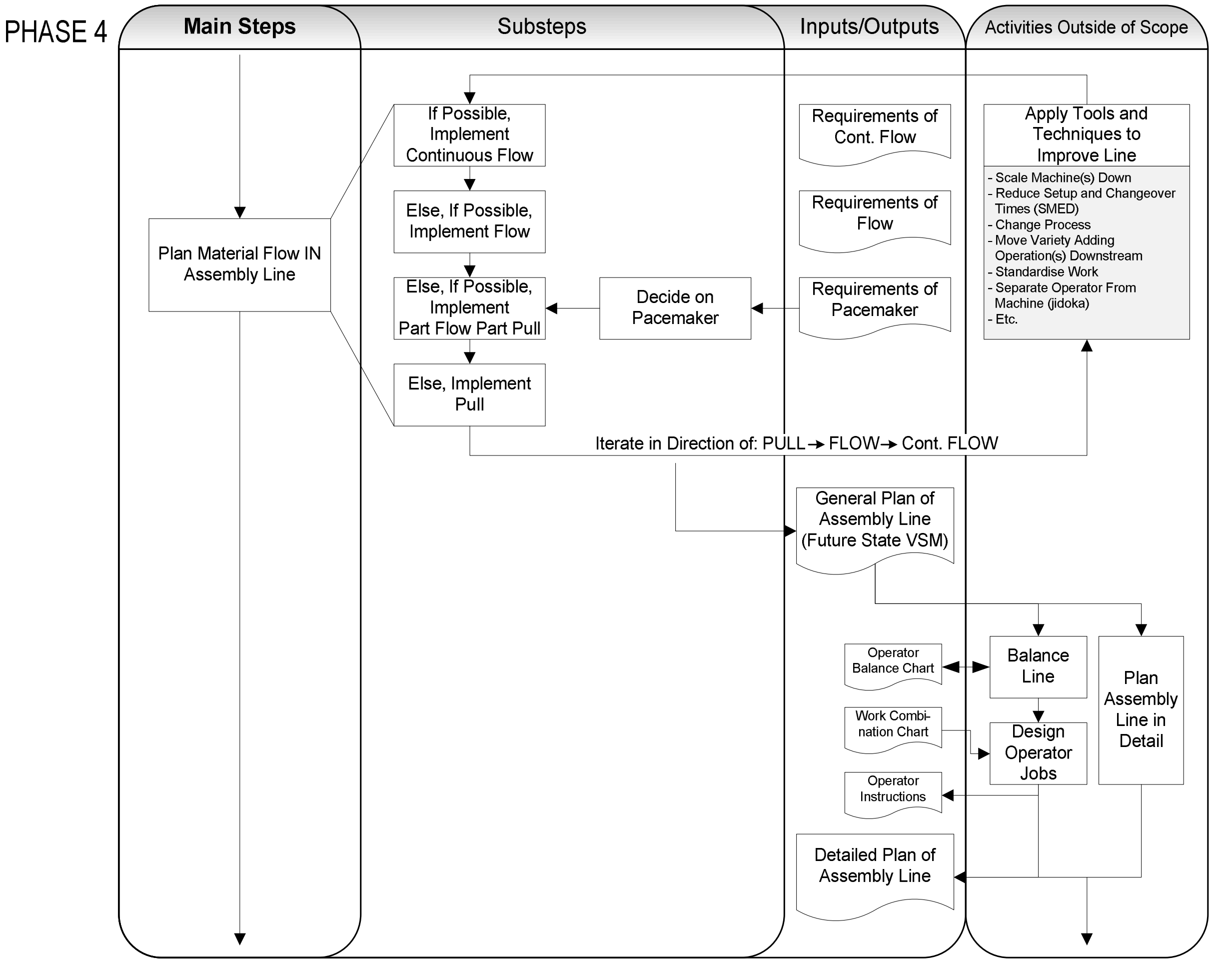

Figure 31: Phase 4 Flowchart.
Note the iterative loop at the top and the mostly assembly-based activities at the lower right.

The general assembly line idea has crystallised, based on an efficient material flow, aiming at an evolution from push to pull to flow and finally to single-piece flow. The needed tools from the Lean Toolbox have been selected. A separate detailed planning has also taken place.

5.8 PHASE 5 – Plan Connecting Material Flows

At this point, we have the completed overview plan (VSM) of the assembly line and detailed plans developed by the separate assembly line planning process. The job of this phase is planning material flow through the value stream by connecting the independent resources that comprise the company's production system. "Independent" in this case refers to all operations that are not connected with single piece continuous flow.

Note: In case the assembly line is already given, do Phase 1 and continue at this phase.

For each separate operation it must be decided how it gets its workpieces, be that from an upstream production process, a warehouse or direct from suppliers. If continuous flow is not possible, choose one of the following possibilities. The list is ordered from best-case to worst-case:

- (continuous flow: direct pull from previous operation)
- FIFO lanes, (flow with buffers)
- Kanban system (pull)
- In-process supermarket (pull)
- Computer-assisted scheduling and commissioning, such as MRP (push)

> **WIPs vs. Parts and Materials**
> Before continuing, there is a fine distinction to be made here, which is important in assembly, but was not explicitly explained in the researched literature. The *works in progress* follow the previously described continuous flow / flow / pull system through the value stream. However, there are also *parts and materials* that need to be built into these WIPs at different points along the assembly line(s). These are provided at the point of use. Their use is controlled by the products being made, which are in turn ordered into the system at the pacemaker process. These parts therefore cannot flow, but must be pulled by the operation that uses them. These differences between the WIPs and the replenishment of separate parts needs to be considered.

Take the following steps for each pair of independent resources that are connected with material flow:

5.8.1 Use Continuous Flow

This can only happen if the operations are near each other and a number of requirements (*Section 2.6.1*) are met, especially highly capable, repeatable and available operations. Continuous flow means that during the material transfer between the two processes, the pieces do not stop for more than a few seconds.

5.8.2 Use FIFO Lane(s)

If continuous flow is not possible, try to connect the two with a FIFO lane, see *Section 2.7.2*.

Choose a FIFO lane:

- In situations where variations in cycle times are preventing single piece flow.
- In high mix, low volume applications, typical made-to-order with mainly manual work.
- Before a batch operation that needs to be separated from the rest of the line, so that the FIFO lane provides the buildup of the necessary batch. But only if the batch operation does not need different settings for different products. Examples:
    - Wash booth,
    - One colour paint booth,
    - Heat treatment.

Do not choose a FIFO lane:

- Before batch operations that require different settings for different products, eg. a paint booth with different colours.
- If requirements of flow in general are not met (see *2.6.2*).

If it cannot be used, the next pull options need to be considered. It is also possible to mix the methods. For example, have a lane for the main module, while provide other parts in a supermarket. During planning this must be decided per part, a good source of information is the Plan for Every Part database.

Design the lane

- Set the maximum number of objects in lane.
    - Minimise the lane to lower inventory and approach one piece flow.
    - Enlarge the lane if there are: larger variations in cycle times of the two processes, low takt time (i.e. high rate of demand), many supplying sources or any unresolved constraints of the system (downtimes, quality issues, long changeovers).
- Size the lane according to parts' sizes/shapes/weights, source: PFEP.
- Set the declination angle (e.g. high for smaller, less sensitive parts; lower for heavy and/or sensitive parts.) Then decide whether the parts can simply slide down or whether rollers are needed.
- Enforce FIFO operation: Make sure workers can only reach the very last part.
- Formulate rules of operation and exception handling: what to do if it is empty, what to do if it is full, etc.

5.8.3 Use a Supermarket Next to Assembly

Choose a Supermarket (described in *Section 2.7.3*):

- If it is not possible to implement flow, some possible reasons being:

  1. *"Cycle times are very different between the two processes. (A process might be very fast or very slow.)*
  2. *A process might have very long change-overs*
  3. *A single process might serve multiple product variations or product families*
  4. *A process might require transportation to another location or sub-contractor*
  5. *A process might have unreliable yields or quality"*[147]

- And if case of not too high product variety, as this would drive inventory costs high. See *Section 2.7.3* for possible solutions.

Do not choose a supermarket:
- For works in progress downstream from the pacemaker process.
- In case of many variants.

Design the Supermarket:
- Decide how many racks are needed.
- Decide how much stock to hold, for example 90 minutes' worth: then multiply the average use of each part with this value to find the needed number of parts.
- Size the racks according to parts' sizes/shapes/weights, source: PFEP.
- Design the gravity racks as in the case of FIFO lanes.
- Formulate rules of operation.

5.8.4 Use Other Kinds of Kanban Supply

Choose Kanban (described in *Section 2.7.4*):

- If the above solutions do not work. *Note: the supermarket was a special case of kanban.*
- For WIPs only if upstream of the pacemaker, or parts supplied from the inbound warehouse irrespective of the pacemaker.

[147] Systems2win: Glossary of Terms for Lean Process Improvement.

Since kanban is the most basic of pull systems discussed here, the requirements of kanban equal the requirements of pull in general. Therefore, **do not choose** Kanban:

- If problems in the production system impede pull, such as:
    - *"Long changeover and machine set-up times...*
    - *Varying production schedules...*
    - *Production variability ... a result of problems in the production process...*
    - *Large batch size...*
    - *A critical bottleneck in the production process...*
    - *Long lead times prevent the produced parts from reaching their destination in time"* [148]
- For WIPs downstream from the pacemaker.

During this planning phase two decisions must be made: first the suitability of these pairs must be checked and second the appropriate kanban system must be selected, as there are different types of kanban, each one being more suited for one particular situation then another. *"In particular the mix, variability, and numbers of resources in the supply chain network (e.g. one-to-many, many-to-many, many-to-one) are key."*[149]

Choose type of Kanban to use

There are several types and variants on Kanban that have been shortly presented in *Section 2.7.5*, the proper one needs to be chosen now. No concrete method has been found in the literature, it is up to the person doing the planning. Some guidelines are:

- For most situation the two card system should work. If the two processes are close together, a one card system is also possible.
- Use the accumulator type when the supplying process can only output larger batches.
- Conwip looks promising, widely quoted benefits are a higher reduction of WIPs and a simple implementation.
- eKanban: whether the benefits of an electronic kanban implementation are worth the costs is up to the decision maker to decide.

Once the type of Kanban system has been chosen, it needs to be designed in specifics. Finding concrete, step-by-step instructions for kanban implementation in the literature proves to be less successful than expected, as Miller puts it:

> *"Why is there no comprehensive, step-by-step book or instruction manual for kanban on the market, in English, yet plenty on kanban-lite? ... Even in Japan, where better books and manuals on kanban are available, there are surprisingly few kanban systems implementation documents."*[150]

[148] McBride, 2004.
[149] SM Thacker & Associates: Kanban Systems, 2009.
[150] Miller, 2009.

However, the following steps can serve as a guide[151]:

1. Position Buffers

Possible positions of the kanban buffer are:

a) at the supplying process,
b) at the receiving process or
c) in-between.

When deciding, consider economies of scale, whether one process is supplying many processes (*a* is better) or many processes are supplying one (*b* is better) or any other constraints.

2. Size Buffers

Note: most sources calculate the number of cards using a previously decided standard container quantity, others such as Weber[152] first size the whole buffer and then divide the pieces into containers.

There are two schools of thought here: either start with a large number of kanbans and eliminate them one at a time (during operation!) or try to calculate the correct number at the start. This latter seems to be the majority opinion. There are many factors that can be considered and many methods have developed here, a list is given in ***Appendix I***. They are mostly based on the following basic formula, whose logic can be easily followed:

$$Number\ of\ Kanbans = \frac{Average\ Use\ During\ Replenishment\ Time + Safety\ Stock}{Container\ Quantity}$$

We have already calculated safety stock before (*Section 5.6.4*), so inserting it, we get:

$$Number\ of\ Kanbans = \frac{AD \cdot LT + SD \cdot Z}{CQ}$$

*(fifth formula in **Appendix I**)*

Where:

AD .... Average Demand in a given time period (e.g. one day)
LT .... Lead Time (from putting the kanban in the kanban post till receiving the ordered material), also called *Replenishment Time*. Use the same unit of measure as the time period for *AD*!
SD .... Standard Deviation of Demand
Z .... Z-value of Service Level
CQ .... Container Quantity, see next step below.

151 Source: SM Thacker & Associates: Kanban Systems, 2009.
152 See: Weber, 2004, pp. 99-101.

Note: the replenishment time is usually equal to two cycle times of the kanban loop: up to one cycle time is needed until the withdrawal kanban is taken from the kanban post, and a second cycle is needed until the parts arrive.

Other factors that might require a larger buffer:

- High product mix, which means the buffer needs to last during the time when the item is not being supplied.
- Long transport time, mainly an issue in inter-factory situations, especially overseas.
- Longer times for system operations, e.g. filling the container or a slow signal.

Some authors describe a more complex calculation of the safety stock, for example Zäh and Möller[153] suggest the following three factors be considered: variation of demand, variation of replenishment time and number of defective parts, see last formula in *Appendix I*. Others take the route of simplification and suggest adding a safety stock equal to half a cycle time or one cycle time of demand. How well the safety stock was determined will only really be seen in operation. Since kanban is flexible in this respect, kanban cards can be added or subtracted from the loop if needed, a faulty calculation is not a large problem (not so in push-systems!).

3. Size Containers

Set the number of parts in a container: the *Container Quantity (CQ)*. For an upper limit, consider the size and weight of parts (PFEP!), that is, not too large containers and not too heavy ones, possibility of manual movement is preferrable. Smaller is usually better but also consider the extra traffic it causes. Take any other influencing factors into account as well.

4. Prioritise Upstream Resources

This is required if one resource supplies more processes and can therefore receive more replenishment signals at once, decide the processing order in such a case.

5. Choose Signalling Mechanism

There are an infinite number of possibilities here. The regular Kanban card (see *Figure 32*) is the most widespread, there are also coloured balls, coloured lamps, bricks, empty containers, tape on floor, voice, EDI, trolleys, eKanban, etc. Choose the one most suited to the task, taking into account distance, speed, volume, complexity.

Design the card. Since there is no standardised way to do it, use common sense and include whatever seems adequate in the given situation. The sample in *Figure 32* includes the part ID, the name and the part type in the middle column, the source and the destination in the top left and right boxes; the quantity in the box and the number of kanbans on the left bottom; the product name in larger letters at the right, underneath it the company name and in small print the date the card was printed.

[153] Zäh, Möller, 2007, pp. 130-131.

Figure 32: Sample kanban card.[154]

6. Verify the Design

Make sure the chosen system with its parameters will work before implementation. The possibilities go from simple "What can go wrong?"-brainstorming sessions through simulation games with lego, all the way to sophisticated computer simulations.

5.8.5 Push System

If the previous four decision steps did not result in a choice for any of the pull systems, the only remaining solution is a push system. In this case the assembly operations are separately scheduled (MRP) and must be supplied with a large buffer inventory. As this solution has many drawbacks and does not conform to the lean principles used as the thesis foundation, this solution will not be discussed further. At any rate, the implementation of lean methods should be possible in any manufacturing system, even if at the cost of first uncovering problems in the system and resolving these.

5.8.6 Decide on Improvement Methods to Use

At this point, the future state map should contain all the operations along the value stream, preferably grouped into cells. All cells and separate operations should be connected by some type of flow or pull system. Most probably a number of improvements are needed to improve flow and reach this planned state. The planning team should select the ones needed and enter them on the VSM in the appropriate place, usually "bursts" are used, see *Figure 3* in *Section 2.5.2*.

Some of the possible methods are 5S, Autonomous Maintenance, Quick Changeover / SMED, implementing standardised work, TPM and others. See the Lean Toolbox in *Section 2.2.3*.

[154] Own drawing, based on an actual card in a manufacturing company (anonymous).

5.8.7 Other Parallel Activities

While the material replenishment is planned, the separate assembly planning has a few jobs as well, such as:

- **Level Production** to produce a smoother material flow and reduce the bullwhip-effect. See *Section 2.7.6* for a common lean solution.
- **Design the assembly cells**: macro and micro design. This is a completely separate topic, please refer to the literature.

Finally, enter the results of planning on the **future-state VSM**:

- Enter the FIFO lane, Supermarket, Kanban and pull icons where needed. Show the route of Kanban cards in each loop.
- If a heijunka board for levelling is decided on, draw this under the Production Control icon on the VSM.
- Enter all material and information routes that are missing. An information arrow should point from Production Control to the pacemaker process.

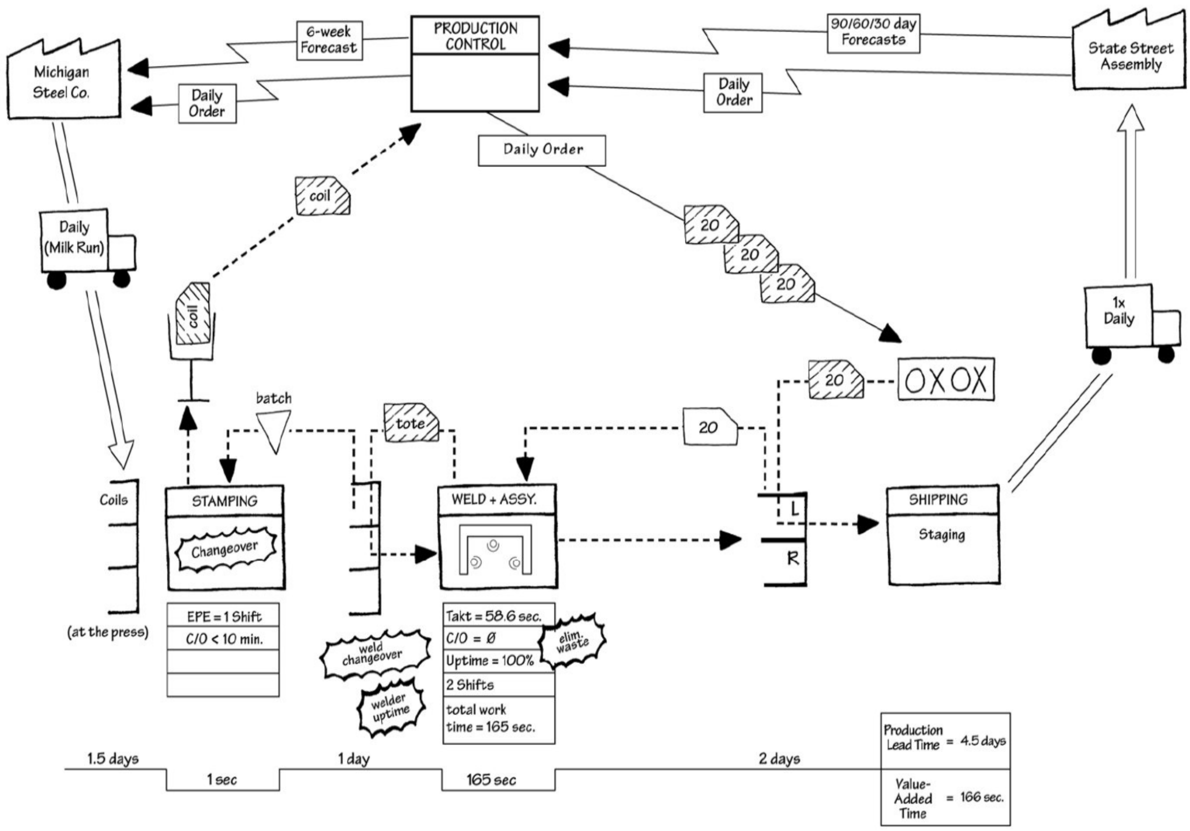

Figure 33: Example future state VSM.[155]

[155] Source: Womack, 2009, p. 38.

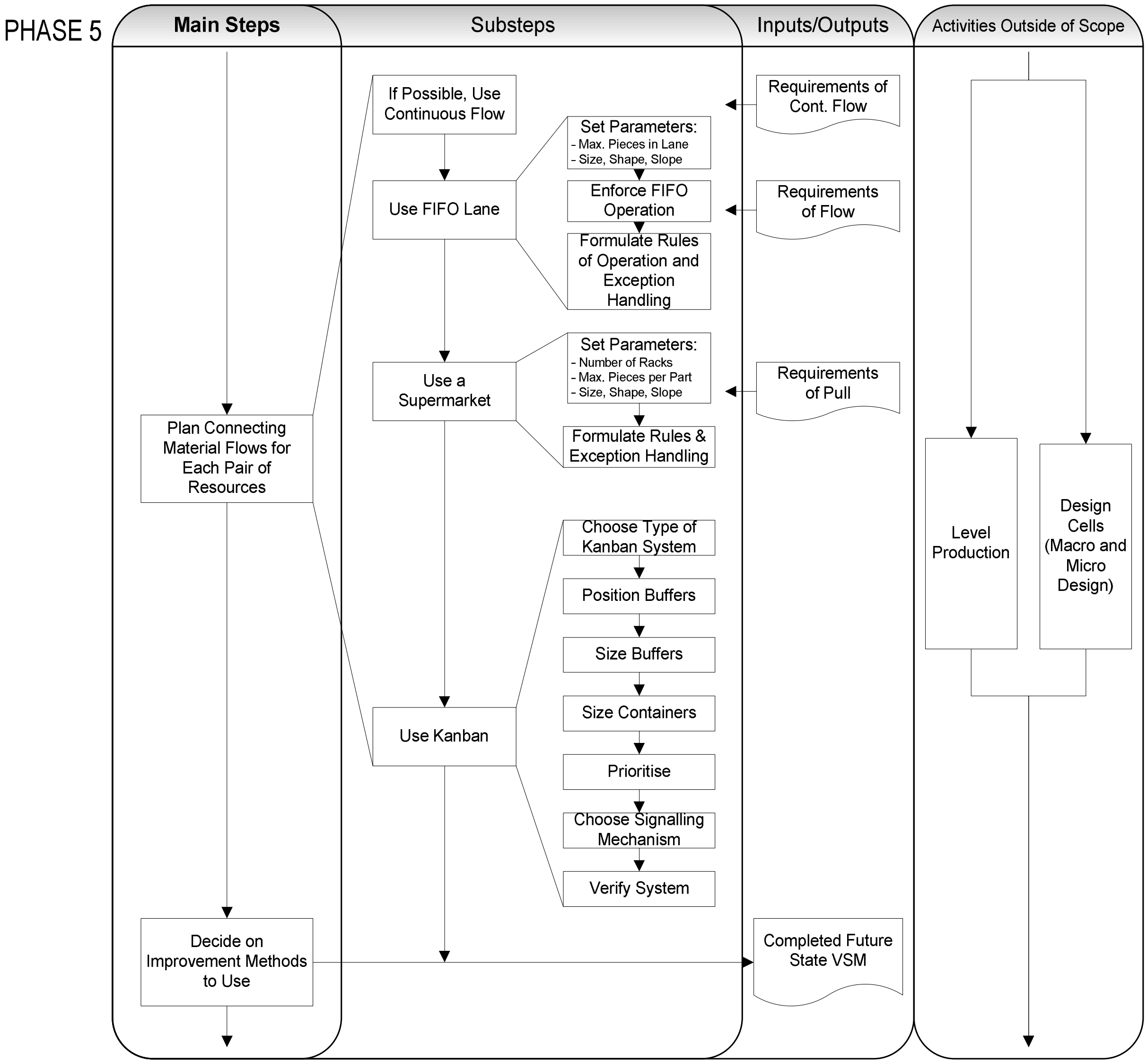

Figure 34: Phase 5 Flowchart.

KEY RESULTS

The material flow method between all elements of the value stream has been determined, the parameters of the replenishment systems used have been calculated. The assembly line design is available.

5.9 PHASE 6 – Plan Material Handling System

The starting situation at this phase: the assembly line planning is finished and documented, including the future-state VSM for overview. There can of course be some unfinished detailed planning activities that are irrelevant to the material flow and can therefore happen parallel with this phase. How the independent resources get their works in progress has also been decided.

Now we take one more step upwards in the value stream and examine the material flow preceding the assembly line. Since the material flow of the WIPs happens inside the line, only the replenishment parts are relevant in this phase.

An assembly line implemented with lean principles requires an adept material handling system to supply it, without which maintaining flow or keeping takt time is difficult. A proper technique for planning a lean material handling system is described by Harris and Harris.[156] The referenced article is short but to the point, its following five steps serve as the base for this phase, while also adding the missing details.

1. *Develop a plan for every part*
2. *Build the purchased-parts market*
3. *Design delivery routes*
4. *Implement pull signals*
5. *Continuously improve the system*

5.9.1 Step 1 – Develop a Plan for Every Part

This step has already been covered in ***Section 5.4***, as it is the foundation of many decisions and calculations during planning. A number of data needs to be gathered for every single part that enters the plant, including physical data, supplier data and others, these are already in the PFEP database.

At this point, it is helpful to **carry out a classification** as seen in *Section 3.2.2*. The two most relevant types seem to be the ABC classification of parts based on value to quantity and XYZ, which shows how much the order frequency varies. These two will help in decisions of the material handling system in this phase, as well as in purchasing. According to Weber[157] a modern ABC classification should be the value of the part combined with the criterion of the replenishment lead time, i.e. how long it takes to procure that part. This means that the B or C parts with very long replenishment times are to be regarded as A parts, those with short lead times remain B-s or C-s. Then, since the in-between class of B is not really meaningful, he argues that in the long run, this middle group should disappear, with most of the B parts wandering over to A, while the "less important" ones to C.

[156] Harris and Harris, 2009.
[157] Weber, 2004, p. 3.

Using this thought process, differentiate the parts into the following two types:

- A parts: high value and/or long replenishment times.
- C parts: low value and short replenishment times.

Most planning methods, including the one described here, focus on the A parts. C-parts management is a separate topic in its own right.[158]

The XYZ classification helps in deciding what type of kanban order each part will have, decide this now if this has not been done yet (for example as part of the scheduling system design). There are two possibilities:

- Order for one part, as an integer multiple of the container quantity – except of course if a variable quantity kanban system was chosen. Use this for the supply of all assembly operations where *"standard"* products are made, that is, frequent runners. These are the X and Y parts.

- Order for a list of parts needed for one product, called a *kitting list*. Use this for *"exotic"*, only sporadically built products, these are the Z parts. For standard parts of rare products, such as screws or wires, the normal part-based orders can be used.

5.9.2 Step 2 – Build the Purchased-Parts Market

After shipment by the suppliers, the purchased parts need to be stored until use in a central location. The lean objective is to minimise the logistics structures, hence the one central location, instead of storing the parts at more locations which is a waste of resources and does not conform to our primary goals. Since one of the central ideas of lean is the reduction of inventory, a lean warehouse should be more centered on material transfer than on material storage, thus the term "market".

Decide on Inbound Stock Ownership

The question arises, whether the parts warehouse and/or the whole parts supply process should be managed by the suppliers. This has become an accepted method today, with solution such as *consignment stock*, *vendor managed inventory*, *top up point of use* and others. There are both benefits such as saving on warehousing, administration costs and bound capital, as inventory belongs to the suppliers until use; but also disadvantages such as the better handling position of the suppliers due to being locked into a relationship. According to one author, *"It is now widely recognised that the benefit is largely in the supplier's hands rather than with the customer."*[159], while other authors emphasize the benefits and 'modernness' of such solutions. In any case, the decision should be made, whether to use such a solution or not.

[158] For a detailed discussion, see Graßy, 2007, p. 178.
[159] SM Thacker & Associates: Materials Management & Stock Control, 2009.

In this planning method, the assumption is made that inbound stock and the supply system belongs to the customer, as "traditionally". This also gives the broadest planning range, as supplier managed stock would require fewer planning steps.

Calculate Stock Parameters

Calculate the minimum inventory level to hold (per part).
The minimum inventory level to hold would be zero in an ideal case, where the production is perfectly consistent and predictable. As there is always variation in demand, a certain buffer inventory (also called *safety stock*) is needed to cover the possible additional consumption of purchased parts. The calculation can happen similar to the buffer inventory created at shipping in *Section 5.6.4.*[160]

$$buffer\ inventory = standard\ deviation(demand)\ \cdot Z\ value(1-\alpha)$$

Where 1-α is the desired service level and the standard deviation (*STD*) is calculated for the time between two replenishments, that is, the lead time. If the STD is given for any other time interval, multiply it with the *square root* of the ratio *lead time : given time interval*. For example, if the variation of the average daily use (ADU) is given and the replenishment arrives weekly:

$$STD_{lead\ time} = STD(ADU)\cdot\sqrt{\frac{7\ days}{1\ day}} = 2{,}646\cdot STD(ADU)$$

Some common Z-values are in the following table.

> *Note*: since the variations less than the average demand are uninteresting, as they do not require safety stock, a one-sided calculation can be used, (rightmost column): so that for the same service level a lower Z value can be chosen.

Z Value	Service Level 1-α (symmetric)	Service Level 1-α/2 (one-sided)
0,50	69,15%	84,57%
1,00	84,13%	92,07%
1,28	90,00%	95,00%
1,64	95,00%	97,50%
2,33	99,00%	99,50%
3,00	99,87%	99,933%
4,00	99,997%	99,998%

Table 5: Common service levels and common Z values

160 Note that there are more complex calculation methods in the literature, look for "inventory management."

Since the on-time delivery rates of the suppliers may be under 100%, provisions should be made for late arrivals of supply. Therefore: enlarge the safety stock for category V and W suppliers (see *Section 3.2.2*). Also take other factors into consideration, such as frequent quality problems with suppliers, breakdowns, strikes, etc. and modify the safety stock accordingly.

Calculate the reorder point

There is a second inventory level that needs to be calculated: the point at which an order is initiated. This is called the *reorder point*, *trigger point* or the *pull trigger point* (PTP) in a lean warehouse. The calculation is simple: the PTP quantity needs to be able to cover the usage of the part until the new order arrives, i.e. during its lead time. Surges in demand are covered with the safety stock, so this is added to the PTP.

$$PTP = ADU \cdot order\ to\ delivery\ lead\ time + Safety\ Stock$$

Calculate the maximum inventory level

When the inventory reaches the PTP, an order is sent to fill it up to the maximum inventory level. Now at this point, decide on either the maximum inventory level, or the order quantity (OQ) and calculate the other term so: $max.\ inv. = PTP + OQ$. Considerations include minimum order quantities, economic order quantities and others.

> *Note:* the last two substeps are just one of several possible methods. The purchasing strategy that is chosen may require other calculations. As inbound logistics is outside the bounds of this thesis, please refer to the literature.

Calculate Space Needed

In this step, calculate the required space for the purchased parts market, based on the calculated maximum inventory levels. Depending on the physical properties of the parts and materials, different storage types can be chosen, basic ones are pallets for large parts and racks for smaller ones. Take the size and weight information from the PFEP database. At this point the separate job of physical warehouse design can be started, parallel to the following activities.

Establish Rules of Operation

Establish Address System

The address system is a logical alphanumeric system for identifying locations in the factory, useful especially in material storage locations. There are many possibilities here, using letters and/or numbers to designate the storage location, inside of this the shelf number and on the shelf the given container rack number. The addresses are used in many places, such as in the PFEP for the locations of parts in the warehouse or in tugger route instructions.

Establish Exception Handling Rules

Decide and specify which actions to take in certain unforeseen situations, such as:

- If minimum stock level is reached. (Initiate a larger order? Review safety stock levels?)
- In case of overshipment.
- In case of late shipment.
- In case of stock-out.
- Etc.

Make sure in such situations not only to react to the given situation but look for possible causes (eg: Five-Why method) and solutions for the future.

Choose Parts Picking Strategy

In case of kanbans for a specific part, one picking order is a one-step operation. The picking strategy is more useful for kitting list kanbans. In this step, choose the picking strategy, which, according to Agarkar contains decisions on the following three policies:[161]

- Choose the pick method, such as: *order picking*, *wave*, *bulk*, or *carton pick*. To consider: quantity per part, number of different parts per order, size and weight of parts and other criteria.
- Choose the cluster size: i.e. how many orders to pick at once. If this is more than one, it is also called *cluster pick* or *batch pick*.
- Choose pick options: either parallel pick in zones and consolidate at the end (*Zone Pick*) or sequential pick across zones (*Pick and Pass*).

Irrespective of method, make sure that parts are picked in first-in-first-out sequence. This step is also connected with warehouse planning, with mutual influencing factors such as creating zones for A, B and C parts. Nyhuis et al. provide several picking and warehouse optimisation strategies.[162]

[161] Agarkar, 2006.
[162] Nyhuis et al., 2006, pp. 338-339.

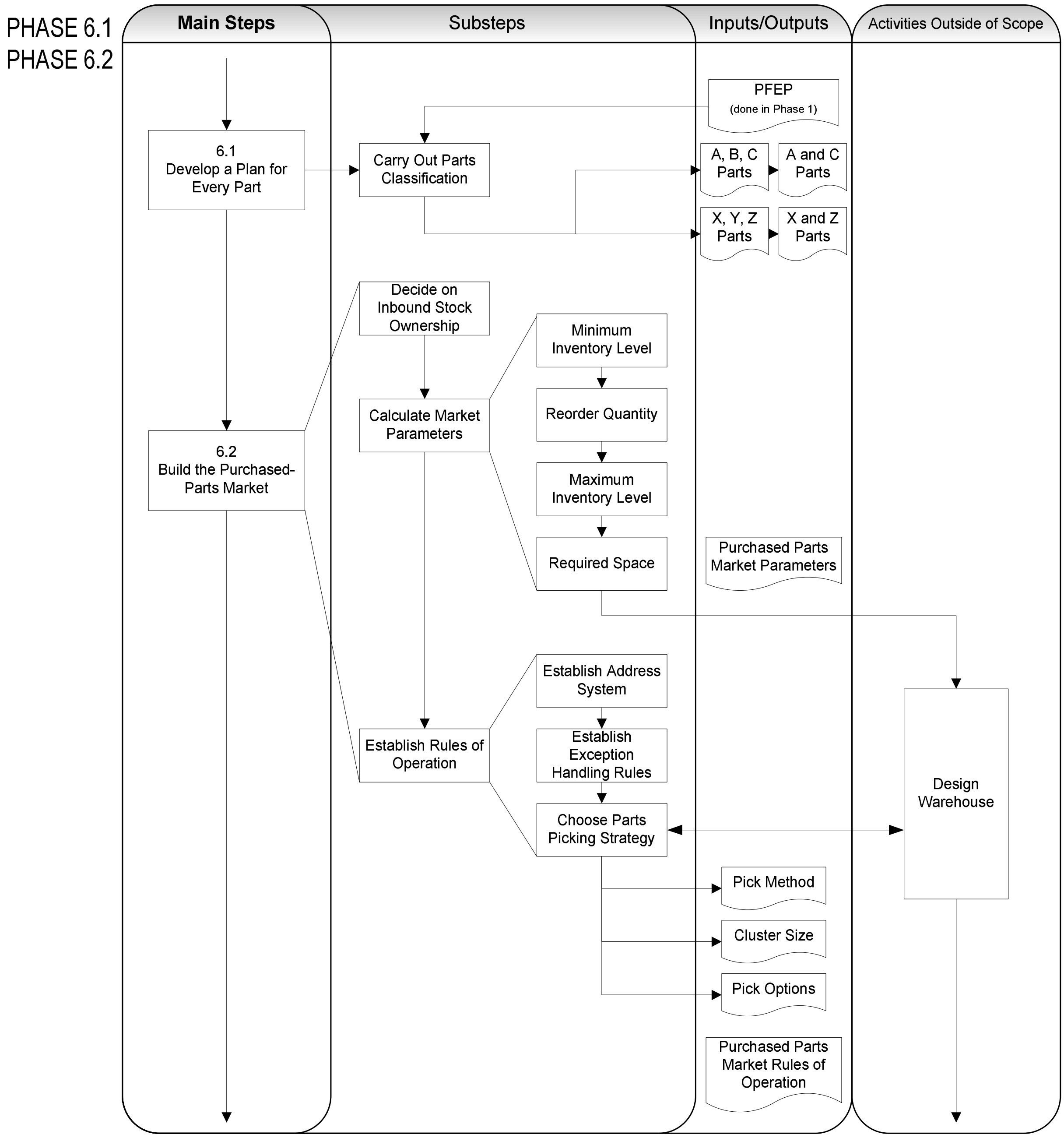

Figure 35: Flowchart of Steps 1 and 2 of Phase 6.

5.9.3 Step 3 – Design Delivery Routes

In this step the infrastructure is designed, which connects the purchased parts market with the parts' point of use. A proper design of the transportation system is a separate topic in its own right, however the main points related to supply planning are discussed below.

1. Select transportation method

This is the basic decision here and will affect the rest of transportation planning. Points to regard are the amount of parts needed in a given time interval, their shape, size, weight, stackability and sensitivity. Especially important to consider is the frequent delivery of small lots according to the just-in-time principle and the fact that several parts should be transported together on a milk-run. This usually rules out moving whole pallets with forklifts, instead of which a common solution in lean supply systems is a "tugger": a usually manually driven cart with one or more trailers. Such a system meets the requirements of delivering many smaller lots at once, while being a low investment and quick to implement. In any case, decide on the appropriate system for the given situation.

2. Identify delivery aisles

Find the physical aisles where the transport from the warehouse can be carried out, this should be available as an outcome of assembly layout planning. Take the physical properties and requirements of the transportation method into consideration, such as width, turning radius, space for loading/unloading, etc.

3. Design transportation

As mentioned before, this is a separate topic outside the thesis' scope, refer to the literature, Piatkowski gives a well summarised implementation plan for tuggers.[163]

4. Determine stops and delivery points on route

The objective of the supply system is to deliver the materials directly to the point of use, the stops should therefore be as close to the supply racks at the assembly line as possible. This leads to many stops, while increasing the stop number increases the time of the route, so a proper compromise needs to be made. Make sure the route length conforms to the delivery frequency in *Step 4* below.

5. Create gravity racks at the point of use

To make a delivery "to the operators' fingertips" possible, implement gravity racks in the assembly cells that are loaded from the outside (delivery points), while the parts are used from the inside.

[163] See: Piatkowski, 2007.

- Determine stock to hold, according to Piatkowski: "*Rule of thumb: start with 2 hours worth of inventory.*"[164]
- Design the racks: size according to stock to hold and container sizes, determine angle and any other characteristics.
- Add a return chute for empty containers that slopes outwards.

6. Determine route of waterspider

If this has not been done before as part of cell planning or assigning the operator tasks, a "*waterspider*" position should be created now to ensure the efficient operation of an assembly cell. The job of this person is to enable the other operators to focus on value adding tasks, by walking along a route at regular intervals, making sure the material supply is not lacking, moving material if needed, moving the kanbans from the containers to the kanban posts and generally managing kanbans and inventory.[165] Determine the route and route frequency of this supporting function now. The frequency should be less than the pitch.[166]

5.9.4 Step 4 – Implement Pull Signals

How the parts are pulled from the purchased parts market, is implemented here, the most widespread lean pull signal being the kanban card. The general kanban loop design has been discussed in *Section 5.8.4*, and its practical implementation for the material flow between in-house production and assembly and inside the assembly line has been considered. This step here serves to design the kanban loops between the inbound market and assembly.

1. Determine delivery frequency

Before getting to the other parameters, the frequency of delivery must be calculated. This applies to all parts delivered by the same tugger. Standard cycle times such as one hour are common. Consider how much material needs to be moved in a given time interval, high material flows might require a higher frequency, half an hour for example. Harris and Harris use a bus analogy:

> *"A good way to prepare people for the change to lean delivery is to compare them to the operation of an efficient bus route. The lean system will drop off passengers (purchased parts) and pick up passengers (empty parts containers, pull signals, and ultimately, finished goods), at regular intervals. In contrast, the traditional system makes material handlers rush around the facility delivering parts based on urgent need, much like a taxi driver driving around looking for fares and moving only one passenger at a time."*[167]

[164] Ibid. p. 2.
[165] The Northwest Lean Networks: Lean Terms & Definitions, 2009.
[166] Tapping et al., 2002, pp. 128-129.
[167] Harris and Harris, 2009.

2. Decide whether route is coupled or decoupled
This means decide whether one person picks the materials from the market and delivers them (coupled) or whether this is divided between two operators (decoupled). In the latter case, one person loads the cart and the other delivers the parts from the market. *"Decoupled routes require two sets of carts but they improve labor utilization, so routes can be longer and have more carts."*[168] This in effect means a second kanban loop inside the market.

3. Calculate number of kanbans needed (for each part)
As already seen in *Section 5.8.4* and *Appendix I*, there are a number of different kanban calculations in use, which however share the same principle. The calculation once more:

$$Number\ of\ Kanbans = \frac{ADU \cdot RT + SD \cdot Z}{SCQ}$$

The replenishment time in a coupled route is equal to **two cycle times**:
- up to one while the kanban waits in the post to be picked up by the tugger,
- and one until the tugger delivers the parts.

The replenishment time in a decoupled route is equal to **three cycle times**: the previous two plus one more cycle in the middle, for the market attendant to prepare the order.

5.9.5 Step 5 – Continuously Improve the System

The final step pursues the fifth stage of lean: continuous improvement. This should be an ongoing process after implementation.

Monitoring activities according to Harris & Harris:
- *"For instance, the production control supervisor should spend about an hour a day observing various elements of the routes and purchased-parts market.*
- *The material-handling team should meet daily to communicate problems and seek solutions.*
- *Key performance metrics focused on such factors as delivery, productivity, and safety should be established for the team.*
- *The daily monitoring must be supported by periodic audits done by overlapping levels of management to make sure that the new tools -- the PFEP, the purchased-parts market, the delivery routes, and the pull signals -- are being maintained and that standard work is being followed.*
- *Emphasize to people that processes, not individual employees, are being audited. Post results for everyone to see."*[169]

[168] Ibid.
[169] Ibid., structured in a list.

Improvement Activities

If the monitoring reveals or employees experience problems, modify the system accordingly, there are many possibilities.

- Replace missing kanbans regularly. Especially when the system is new, they can often go missing; however, printing a new one takes no time at all.
- Add kanbans to a loop if there are stock-outs.
- Remove kanbans from a loop to decrease works in progress.
- Modify container size: decrease it to enable more precise supply and lower WIP quantities, increase it if it causes too much transportation.

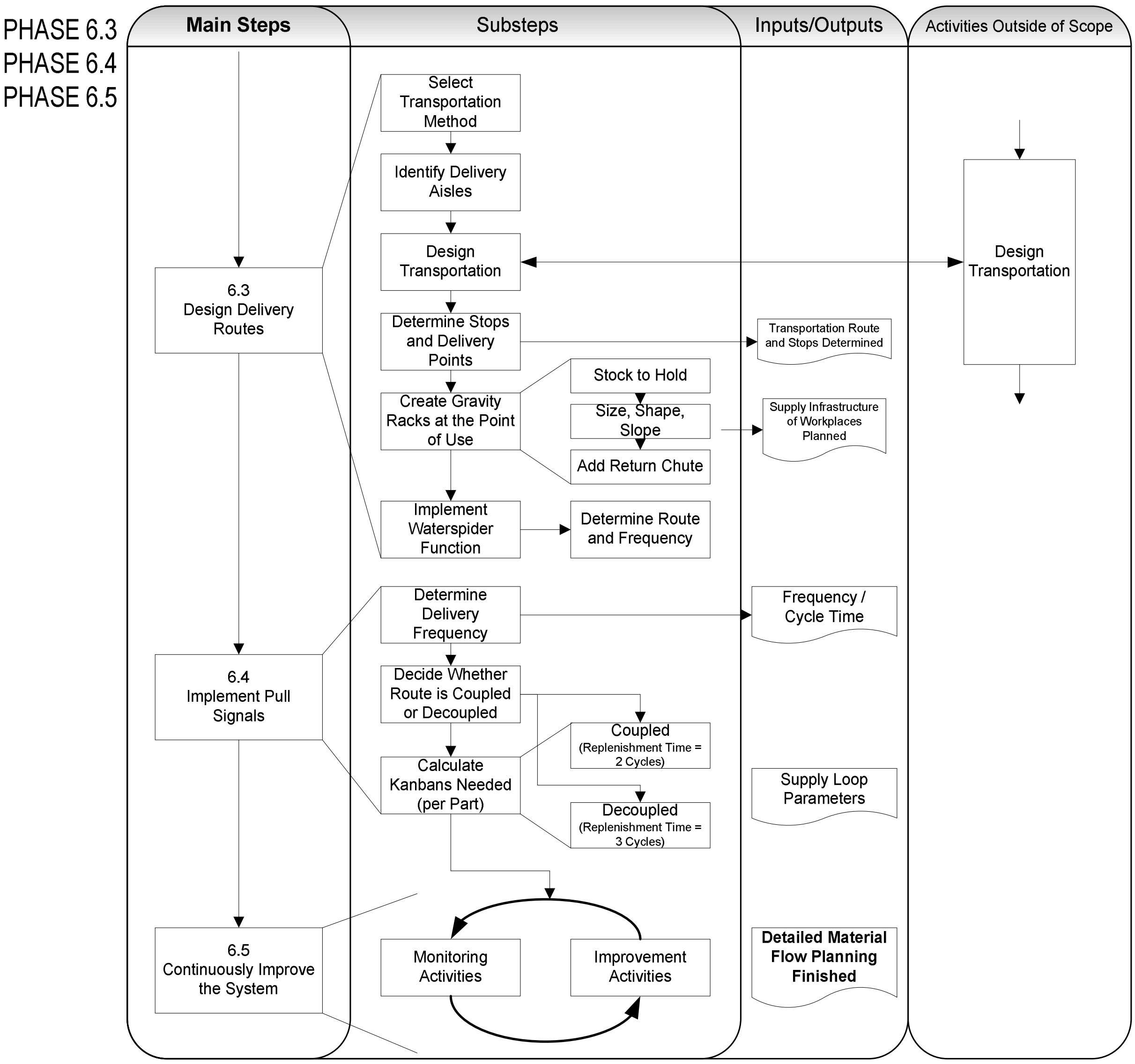

Figure 36: Flowchart of Steps 3, 4 and 5 of Phase 6.

By the end of this phase, the whole material flow has been planned: the purchased parts market designed, the pull-based supply loops between the market and the operations in the assembly line determined, including all parameters. The delivery system has been planned and all other characteristics of the material handling system. The foundation for future monitoring and improvement activities have been laid.

5.10 PHASE 7 – Plan Purchasing

The material flow inside the company starting from the customer needs upwards to the purchased parts market has been designed. The next step upwards along the value stream would be inbound logistics: planning the purchasing strategies, setting policies for selecting suppliers, transportation planning and other activities. At this point however, we have reached the limits of the thesis, inbound logistics falls outside of scope. There are various sources on these topics in the literature, in accordance with modern methods of supply chain management and lean.

5.11 Implementation Phase

After overviewing the redesigned assembly line and material flow and all associated changes and wrapping up the planning stage, the implementation of the future state must be planned. How is the company going to go from the current state to the future state, while continually maintaining production? The concrete phases and steps to take are planned in this step, including measures to take, due dates and responsibilities. These measures are then carried out. The introduction of lean will require the involvement of the whole enterprise, from top management to the line workers. Implementing just one tool or another from the lean toolbox will not bring all the possible benefits, the whole concept needs to be realised. It is a good idea therefore to start small and expand, for example create a cell for one product family only, make sure it works, all the while training the employees in the new system and gaining experience. Then using the inertia gained from the first line, transform the others.

Tapping et al. suggest creating a monthly kaizen plan for specific stages in implementation, as a macro-level structure. Then the main elements can be broken into milestones (definable activities or tasks) and entered onto a *kaizen milestone worksheet*, with start dates, expected due dates and real completion dates, as well as other documenting information.[170] An example assessment of the current degree of lean implementation in a company is given in ***Appendix II***.

As this step is not part of the thesis' scope, see the literature for more, especially the tools of project and change management.

Perfection

Finally, one should keep a vision of the ideal process in mind and continuously improve the assembly system in this direction. Activities such as *kaizen* and *kaikaku* (see *Section 2.8*) can help along this path towards "*perfection*".

[170] Tapping et al., 2002, pp. 137-140.

6 Conclusion

There were basically two lessons gained from the literature review. For one, Chapter 4 showed that there are several different planning methods in the literature, but that none of them seem to fit the thesis subject, or consider all of the factors that were deemed important. The second was that in spite of this, many sources are available about the concrete techniques that do consider the factors and can reach the appointed goals. The missing link is a planning method to structure the available information into a step-by-step planning guide.

The best method or toolkit of methods seemed to be lean manufacturing, which was introduced in Chapter 2. Its subject areas most relevant to material flow planning in assembly lines were also described in more detail here. A new planning method based on these foundations was formulated in Chapter 5, attempting on the one hand to keep the focus on the subject, while on the other hand referring to the many branches and other parallel activities throughout the project. References to additional information in the literature were given throughout the various phases. The principles of specifying a value in terms of the customers' needs, creating a waste-free value stream from suppliers to customer, making the value flow, using a material flow system based on pull and concentrating on a long term vision of perfection will then enable the manufacturing company in creating a world-class assembly line and meeting and exceeding all the high expectations from the introduction.

7 Closing Thoughts

I feel the decision to widen the scope of the originally proposed subject was the right one, as it seems that such a focused design of just one subsystem cannot be as effective as a parallel design of the whole system. However, the further one goes along this thinking, the more broad the topic becomes, and concentration was needed on my part to keep the thesis' focus. Some subjects I left out with regret. Either these, or the numerous other parallel activities, especially in the area of assembly line planning could be good candidates for other research papers.

While I do not assert that the formulated planning method is the only way, or even that it is better than other ways; I do feel it rests on a solid foundation and is a functioning method.

Finally, I must say that the techniques of lean have been intriguing, with motivating stories and anecdotes and great achievements. Its principles and tools are thought-provoking and fascinating in their simplicity, yet able to solve complex problems. The lesson one learns is that simpler is better, and that it is worth constantly attempting to improve oneself and one's environment. And do not only "*attempt*", but *"Just do it!"*.

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List of Tables and Figures

Appendix I – Kanban Calculations[171]

Note: the original abbreviations have been unified to enable a comparison

Abbreviations used:

AD ....Average Demand (Average Consumption) in a time period [pieces/same time unit as LT]
CQ ....Container Quantity (aka. Kanban Size)
D..................Demand
EPEI............Every Part Every Interval
LT ....Lead Time = Replenishment Time [day, hour, etc.]
SD................Standard Deviation of Demand during replenishment time
SF ....Safety Factor
SS.................Safety Stock (independent of how it is calculated)
ST.................Safety Time
TB ...."*Time bucket of the safety stock data points (days)*"
Z...................Z value of desired service level

μ_D.................= AD = Average Demand
μ_{LT} ....= LT = (Average) Lead Time
μ_Q.................Average Number of Non-Defective Parts per Lot
σ_D.................= SD = Standard Deviation of Demand
σ_{LT} ....Standard Deviation of Lead Time
σ_Q.................Standard Deviation of the Number of Non-defective Parts per Lot

$$No.of\ Kanban = \frac{AD \cdot LT + SS \cdot \sqrt{\frac{LT}{TB}}}{CQ} + \frac{ADU \cdot EPEI}{CQ}$$

$$No.of\ Kanban = \frac{AD \cdot (LT + SS)}{CQ} + 1$$

$$Total\ Required\ Inventory = AD \cdot LT + 1or2\ sigma + SS$$

$$Total\ Required\ Inventory = \frac{AD \cdot LT \cdot 1.X}{CQ}, where\ X = 20 - 40\%$$

$$No.of\ Kanban = \frac{AD \cdot LT + SD \cdot Z}{CQ}$$

[171] Source of the first 11: Kanban Calculation, 2006, http://www.resourcesystemsconsulting.com/blog/archives/58 and
More Kanban Calculations, 2009, http://www.resourcesystemsconsulting.com/blog/archives/495

$$No.of\ Kanban = \frac{AD \cdot LT + SS}{CQ}$$

$$No.of\ Kanban = \frac{D(per\ hour) \cdot LT(in\ hours) + SS}{CQ}$$

$$No.of\ Kanban = \frac{AD \cdot (RunFrequency[days] + LT + ST)}{CQ}$$

$$No.of\ Kanban = \frac{Weekly\ Part\ Usage \cdot LT \cdot Number\ of\ Locations\ for\ Stock}{CQ}$$

Used in Oracle:[172]

$$(No.of\ Kanban - 1) \cdot CQ = AD \cdot LT$$

Used in SAP:[173]

$$No.of\ Kanban = \frac{LT \cdot AD}{CQ} \cdot SF + C, where\ C = constant(default: 1)$$

According to Zäh and Möller:[174]

$$No.of\ Kanban = \frac{AD \cdot LT}{CQ} + Z\sqrt{{\sigma_D}^2 \cdot \mu_{LT} + {\mu_D}^2 \cdot \sigma_{LT} + {\sigma_Q}^2 \cdot \mu_D \cdot \frac{\mu_{LT}}{\mu_Q}}$$

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172 Oracle: Overview of Kanban Planning, http://download.oracle.com/docs/cd/A60725_05/html/comnls/us/mrp/kbovw.htm (accessed on: 22.09.2009)
173 SAP: Calculating the Number of Kanbans/Kanban Quantity, http://help.sap.com/saphelp_40b/helpdata/en/cb/7f8c3943b711d189410000e829fbbd/content.htm (accessed on: 22.09.2009)
174 Zäh, Möller, 2007, pp 128-131.

Appendix II – Sample Value Stream Assessment[175]

For the Implementation Phase (*Section 5.11*)

BU Assessment — **Assessment Date:** 12-Jul-06

XYZ Value Stream — **Start Date:** Oct-06

ABC Value Stream — **Start Date:** Mar-06

	Area of Concentration	Expectations (Description)	XYZ Implementation 25%	50%	75%	100%	XYZ Sustainment 1	2	3	ABC Implementation 25%	50%	75%	100%	ABC Sustainment 1	2	3
Value Stream Mapping																
1	Product Family Matrix	Products are sorted into families based on similarities of processing steps.														
2	Value Stream Mapping	Current & Future State maps & Implementation Plan posted and up to date.														
Takt Time																
3	Takt Time Calculation	Takt time calculated for average annual demand rate.														
Interval																
4	Interval Analysis	Interval analysis used to determine machine capabilities.														
5	Quick Changeover	Changeover times are reduced to accommodate a shorter interval.														
Single Piece Flow																
6a	Operator Balancing	Work Elements collected for initial single piece flow cell														
7a	Layout Implementation	Single piece flow implemented, monitored and debugged.														
8a	Standard Work (Level 1)	Standard Work for the build process created and posted. Use balance charts as base.														
6b	Operator Balancing	Work Elements collected for initial single piece flow cell														
7b	Layout Implementation	Single piece flow implemented, monitored and debugged.														
8b	Standard Work (Level 1)	Standard Work for the build process created and posted. Use balance charts as base.														
FIFO																
9a	FIFO Lanes	FIFO lane implemented to control inventory between two processes.														
9b	FIFO Lanes	FIFO lane implemented to control inventory between two processes.														
10	FIFO Standard Work (Level 2)	Standard Work created and posted. Includes actions for full and empty conditions.														
Finished Goods Strategy																
11	Finsished Goods Strategy	Finished goods strategy validated, implemented and in use.														
Pull																
12	Pacemaker Supermarket	Component parts used at the pacemaker process are replenished using Pull.														
13	Waterspider	Material delivery route to deliver product to (and take away from) the pacemaker process.														
14	Waterspider Standard Work (Level 2)	Material replenishment Standard Work created and posted.														
15	Process Family Matrix	Upstream processes are grouped into families. Shared resources are dedicated to create flow.														
16	Value Stream Supermarkets	All value stream component parts are replenished using Pull.														
17	Initial Raw Stock Supermarkets	10 raw stock part numbers ordered from suppliers using a Pull system (e.g. kanban).														
18	Value Stream Raw Stock Supermarkets	All raw stock part numbers ordered from suppliers using a Pull system (e.g. kanban).														
Scheduling																
19	Single Point Scheduling	Value stream scheduled at a single point in pitch increments.														
20	Scheduling Standard Work (Level 2)	Scheduling standard Work created and posted.														
Pitch																
21	Pitch	Value stream monitored at regular pitch increments to ensure customer demand met.														
22	Metrics	5-8 key metrics posted on cell, value stream, and site boards.														
23	Pitch Standard Work (Level 2)	Standard Work created and posted for how to track pitch.														
24	Missed Pitch Standard Work (Level 3)	Standard Work created and posted to get value stream on pace after missing pitch.														
Perfection																
25	Value Stream Mapping	Next iteration Current & Future State maps & Implementation Plan posted and up to date.														
26	5S / 6S	5S implemented to further reduce waste within the value stream.														
27	Visual Flow	Product flow is visible throughout the facility to the untrained eye.														
28	Value Stream Focus	Support functions (sales, engineering, etc.) are assigned to value streams														

COLOR CODING

No Expectation	The value stream is not yet expected to be at this level of implementation.
Expectations Achieved	Once all expectations are met, the appropriate box is colored green.
Expected Score	Yellow can be used to indicate where the facility should be.
Previous Score	If a value stream regresses, then the previous score is colored red.
Not Applicable	If a category does not apply to the value stream, the boxes are colored grey.

[175] Source: Lean Solutions Limited: Sample Production VS Assessment, 2006.