DESIGNING MIXED-MODEL ASSEMBLY LINES: A LITERATURE REVIEW

- FINAL REPORT -

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As Literature Assignment
For Delft University of Technology, The Netherlands
At Osaka University, Japan
On August 21st, 2009
Preface

This report is written as part of my Masters in Production Engineering and Logistics at Delft University of Technology, the Netherlands. The main objective of this literature assignment is to gain knowledge on a certain topic related to this specialization.

I am very fortunate to be able to do this as an exchange research student at Osaka University in Japan, thanks to the IGM exchange program by Professor Tomiyama. With this program I joined the Fujita laboratory in Osaka, who’s research topics are related to Mass Customization.

Being at the Fujita laboratory inspired me to have a look beyond my own field, into the world of Design Engineering on a product level. However, my own research had to be focussed on the production level. This is how I finally came up with the research topic, which is an extension to the work done by Prof Fujita and his students, and is more related to my own specialization. This way I hope the report will be useful for both parties.

The total duration of this research project is about 4 months. It will be credited as 12 ECTS.

August 21st, 2009

Osaka, Japan

Rogier de Jong
Abstract

This report describes a research assignment done on what’s written about designing mixed-model assembly lines.

First the general context is explained by looking at how assembly evolved throughout history. This goes back to about a century ago, when Henry Ford started the first mass production assembly line in 1913. Since then, customers started asking for products that were more customized to their specific needs. That’s how the world of production shifted from single-model mass production lines to mass customized mixed-model assembly lines where complete product families can be assembled in any one-piece sequence, according to short term sales forecasts.

After that the basic terms and definitions are given. An assembly line consists of a finite set of work elements or tasks usually arranged along a conveyor belt or a similar mechanical material handling equipment, and each having an operation processing time and a set of precedence relations, which specify the sequence in which the product has to be assembled. This can be done in many variations, which are best classified by a scheme developed by Boysen, Fliedner et al. This classification scheme became a guide for this report.

Once this is all known, we get into more detail on how assembly lines work in general, and especially what the difficulties are in operating and designing them. This leads us to the first and most basic design approach: load balancing. This is done to apportion the total assembly work among the stations or operators on the line as evenly and compactly as possible, or for any other objective like minimizing the cycle time or the costs.

We then focus specifically on the mixed-model assembly line design problem, where more variables have to be determined. The most common one is the sequence of models that are launched down the line. This procedure is called model sequencing, and is done either to smoothen the workload of the different models among the stations, or it can be done to smoothen the material and part usage. The sequencing is done after the line is balanced to a virtual average model, and has a shorter planning horizon.

A lot of methodologies have been published on balancing-sequencing mixed model assembly lines. The most important ones are introduced, together with currently available software tools.

Once this is all done, an interesting fact is found. A number of recent papers look back on what’s published in the scientific world so far and what is done by industrial practitioners in the real world. This makes clear that their is still a gap between both parties. The real world cases are more complex than the methodologies developed, so industrial planners usually don’t use them but rather base their design on experience. It can easily been shown however, that no assembly line is similar, and that even the slightest change in characteristics can make a big difference. It is thus important that this gap will be closed soon, to be able to ultimately reach the optimal methodology for designing mixed-model assembly lines. This design methodology should of course include load balancing and model sequencing, but also processing alternatives, flexible station and line characteristics and parallel and team working.
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Introduction

As soon as I had the choice to go to Japan, I was certain to go there to find out more about the famous Japanese production systems I'd heard so much about. I chose the Fujita laboratory because one of their research topics was on “Mass Customization”, a topic that already got my interest before. And although the actual research there was done more on a product level, it was a good chance for me to explore the production level on my own.

So, the initial idea started with an open view on “How do they do that?”, i.e. “How do you produce all these similar (but not the same) products?”. During the research this question gradually got more defined. The exact way on how this exploration continued can be found in Appendix I.

After some reading I soon came up with the following sub-questions:

- Why are mixed-model assembly lines being used?
- What are mixed-model assembly lines?
- What are the difficulties in designing and operating mixed-model assembly lines?
- What are the theories on designing mixed-model assembly lines?
- How is it done in the real world?

This became the main guideline for this report.

Scope

To make this research more clear and understandable, some “system boundaries” have to be defined first.

- This report functions as an overview of what is written about the design of mixed-model assembly lines.
- No new methods will be developed, it is purely observation of current methodologies.
- To make it understandable for everyone, the general context is included as well.
- For in-depth details on the referred quotes and methodologies, please see the papers themselves.
- The main focus will be on mixed-model assembly lines, although the basics will be derived from single model line design theories.
1. Why mixed-model assembly lines?

To be able to place this research in the right context, we first take a look at the “Why” question. This is done by a historic overview of one of the largest manufacturing industries world wide: the automobile industry. This leads us to the current state of demand and the consequences for the supply and thus production.

1.1 The history of assembly

*From craftsmen to mass production (1700 - 1910)*

In the beginning of the 20th century Henry Ford caused a big change in the world of production. While the real roots of assembly lines go further back in history, the Ford Model T car assembly line (Fig 1) is the classic example of how craftsmanship changed into mass production (Fig 2), causing the lead time of a car chassis to decrease from 12.5 hours to 93 minutes. This helped the production costs to decrease to such a level that cars became reasonably priced for the majority of people for the first time.

![Fig 1. An old photo of the Ford Model T assembly line.](image)

The largest cost reducing advantages of these assembly lines were (and are) (Bukchin, Dar-El et al. 2001):

- **Less resources needed**
  Because the products move along all of the workstations, tools and machines only have to be bought once, instead of each station having all the tools and machines to make the product at once.

- **Cheaper labour**
  Since each operator performs the same task on all products every time, he/she doesn’t have to be multi-skilled. Therefore wages can be low.

- **Learning effect**
  Thanks to the repetitive work, workers get specialized on performing their tasks and gradually
get faster in performing them. This is called the learning effect, and causes the total assembly time to decrease.

<table>
<thead>
<tr>
<th>1700–1850</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craft/cottage production (no system design)</td>
</tr>
<tr>
<td>○ Craftsmen: Blacksmiths, silversmiths, wheelwrights, tailors, etc.</td>
</tr>
<tr>
<td>1840–1910</td>
</tr>
<tr>
<td>○ First industrial revolution (American armory system)</td>
</tr>
<tr>
<td>○ Creation of factories with powered machines</td>
</tr>
<tr>
<td>○ Mechanization/interchangeable parts</td>
</tr>
<tr>
<td>○ Job shop/functional layout</td>
</tr>
<tr>
<td>1910–1970</td>
</tr>
<tr>
<td>○ Second industrial revolution (Ford production system)</td>
</tr>
<tr>
<td>○ Moving assembly line: Flow shop product layout</td>
</tr>
<tr>
<td>○ Economy of scale/mass production (Ford) era</td>
</tr>
<tr>
<td>○ Automation (automatic material handling)</td>
</tr>
<tr>
<td>1960–2007 and counting</td>
</tr>
<tr>
<td>○ Third industrial revolution (Toyota Production System)</td>
</tr>
<tr>
<td>○ Lean production: JIT/TQC-WCM</td>
</tr>
<tr>
<td>○ Linked-cell manufacturing system design</td>
</tr>
<tr>
<td>○ Simpler, lowest cost, higher superior quality, flexibility</td>
</tr>
<tr>
<td>○ Integrated control functions: Kanban, pull</td>
</tr>
</tbody>
</table>

The downsides of using assembly lines are however (Bukchin, Darel et al. 1997):

- **Low flexibility**
  A mass production line is designed and optimized for one particular product. If considerable changes to the product are required, a whole new line has to be designed and installed.

- **High balance loss**
  Caused by different task times and stochastic variation of humans versus the paced line speed, some workers do more than others, so there is a loss in utilization.

- **Poor quality**
  There is no direct link between the worker and the final product, no feedback is given, and the worker cannot learn from his or her mistakes.

- **Poor working environment**
  Workers will have to do the same (simple) task every day, all day, almost like a machine. This will eventually lead to high worker turnover because of the lack of work satisfaction.

- **High work in progress**
  Assembly lines require long flow times due to the sequential order of the assembly operations. This, together with safety stocks, causes a lot of work-in-progress.

- **High costs of material handling**
  Since the workers are stationary at their station, materials have to be moved along the entire line.

**From single model to mixed-model assembly (1910 - 1960)**

A famous one-liner for the Ford revolution is that “You could buy any car as long as it’s black Ford Model T” (Bukchin, Dar-El et al. 2001), meaning that this first mass production assembly line was only capable of producing one type of car: a black Ford Model T. From now on this one-type production will be called a Single-model assembly line (see Fig 4 a.).
During this first period of mass production, people were so happy that they could finally buy a car, that they didn’t mind the color or whatsoever. But times changed, and customers started asking for specific features. What most people don’t know, is that Ford also responded to this and was actually one of the first manufacturers to design their products in a modular way (Alizon, Shooter et al. 2009). This was done by using a so-called “skateboard design”, which uses the same platform combined with different modules (like 2/4 seats and left/right steering) on top. This concept is still being used by car manufacturers today (Fig 3).

Using this modular design, different variations of the same base model could be made to satisfy the customers needs, with similar production effort. This principle is nowadays called Mass customization.

Because of the similarity in design, it was possible to assemble the different models on the same line after adjusting some of the settings. This was first done in batches of a particular size according to sales forecasts for a particular time frame, making it a Multi-model assembly line (see Fig 4 c.). A major disadvantage of this was that large stocks of finished goods were required to cover the entire forecasted period, and the over- or underproduction when forecasts weren’t accurate enough.
When Japanese car manufacturers started to arise, they went to the US to learn from the already large automotive industry over there. After copying most of the US systems to their own factories, they realized that they had to improve to be competitive with the American cars. This was mainly because costs for raw materials and land were much higher in Japan. In the first publication from the top management of Toyota themselves about their production system (Sugimori, Kusunoki et al. 1977) they state:

*To overcome this handicap, it is essential for the Japanese industries to put forth their best efforts in order to produce better quality goods having higher added value and at an even lower production cost than those of the other countries.*

(Sugimori, Kusunoki et al. 1977)

That’s how the Just-In-Time production really started at the Toyota Motor Company, as part of the wider field of Lean, which main objective is to eliminate all forms of waste. Just-In-Time itself focuses on producing only the right products at the right time in the right quantity. One of the ways to accomplish this is to design the production system in a way that made it possible to decrease the batch size to one, i.e. one piece production, so minimum stock was needed. That was the beginning of the Mixed-model assembly lines (Fig 4 b.) that are able to produce any sequence of models without significant setup times in between.

**Flexible, high quality, low cost mixed-model assembly (1960 - current)**

Eventually, the success of the Japanese car manufacturers gained a lot of attention, especially thanks to an extensive research on Lean Manufacturing by Womack, Jones et al. (1990). So today mixed-model assembly lines can be found all over the world (Fig 5), and in many different industries (Fig 6). With the growing trend for greater product variability and shorter life cycle, they are gradually replacing the traditional single model mass production assembly lines (Bukchin, Dar-El et al. 2001).
Fig 5. Output of a modern German car assembly line. From the outside it can already be seen that silver and red cars are mixed, but other aspects like engines and interior may differ as well.

Examples of real one-piece mixed-model assembly lines in other industries are for instance the production of user-customized products like the computers at Dell or the highly season dependent products like air conditioners at Daikin (see Chapter 5). Also the assembly of components on printed circuit boards and the production of furniture can be done in a mixed-model way nowadays (Fig 6).

Fig 6. An illustration of a mixed-model assembly line with 4 models of cabinet (Sarker and Pan 2001).

1.2 About mass customization

Mass customization aims to provide customer satisfaction with increasing variety and customization without a corresponding increase in cost and lead time. It emphasizes the economies of scope, rather than the old paradigm of mass production to mass produce standardized products through economies of scale (Tseng and Jiao 1996).

To be able to do this, companies develop platform-based products tailored to customers’ needs through derivative products (Alizon, Shooter et al. 2009). A group of these derivative products is often called a product family.

A product family refers to a set of similar products that are derived from a common platform and yet possess specific features/functionality to meet particular customer requirements. Each individual product within a product family, i.e., a family member, is called a product variant. While a product family targets a certain market segment, each product variant is developed to address a specific set
of customer needs within the market segment. All product variants share some common structures and/or common product technologies, which form the platform of the product family. Developing product families has been recognized as an effective means to achieve mass customization goals.
(Du, Jiao et al. 2001)

This platform-based product design approach has multiple advantages (Robertson and Ulrich 1998):

• Greater ability to tailor products to the needs of different market segments or customers
• Reduced development cost and time
• Reduced manufacturing cost
• Reduced production investment
• Reduced systemic complexity
• Lower risk
• Improved service

It will thus enable companies to increase their market share and reduce their development and manufacturing costs at the same time. That’s why mass customization can nowadays be seen at companies in all different kinds of industries.

While this sounds very simple and seems to only have advantages, practicing mass customization in real life isn’t that easy. Instead of designing one particular product on its own, companies are now designing complete product-families at once. This means that they are working on a higher level (echelon) and with larger teams. This requires a new form of control, called platform planning (Robertson and Ulrich 1998).

Overall, a lot of research has been done on topics related to mass customization and platform-based product design. Du, Jiao, et al. (2001) is a good reference for further information. Professor Fujita’s work is also cited a lot, regarding to his work on product family architecture and variety design and fulfillment (Fujita and Yoshida 2001; Fujita 2002).

The following chapters of this report will focus on mass customization and thus mixed-model assembly lines, because this way of production is the most challenging and is nowadays used by a lot of companies. However, mass customization and product family design itself will not further be discussed in this report.
2. What are mixed-model assembly lines?

Now that we know why we need mixed-model assembly lines, it’s time to find out more about them. To do so, we first take a step back and look at the general definitions of assembly lines and everything related. After that, an overview of characteristics will be given. This way we will find out exactly what we are talking about.

2.1 Assembly lines in general

Obviously, a lot has been written about assembly lines since the beginning of the 20th century.

Assembly lines can be describes as:

\[
\text{In its basic form, an assembly line consists of a finite set of work elements or tasks, each having an operation processing time and a set of precedence relations, which specify the permissible orderings of the tasks.}
\]

(Ghosh and Gagnon 1989)

An assembly line consists of (work) stations \( k = 1, ..., m \) usually arranged along a conveyor belt or a similar mechanical material handling equipment. The workpieces (jobs) are consecutively launched down the line and are moved from station to station. At each station, certain operations are repeatedly performed regarding the cycle time (maximum or average time available for each work cycle).

(Boysen, Fliedner et al. 2008)

Common terminology used when talking about assembly lines are:

Work element (or task)

A minimum rational work element is an indivisible work unit, beyond which assembly work cannot be divided rationally. For example, a minimum element may include the following motions: reach to a tool, grasp it, move it into position, perform a single task, return the tool. In practice such work elements are considered indivisible, since they cannot be divided or split between two operators without creating unnecessary work in the form of extra handling.

(Kilbridge and Wester 1962)

Workstation (and operator)

A work station is an assigned location where a given amount of work is performed. Assembly line work stations are generally manned by one operator. In some situations, however, an operator may man more than one station, and on lines making large products (automobiles, for example) work stations are frequently manned by several operators.

(Kilbridge and Wester 1962)

Cycle time

The cycle time is the time the product spends at each work station on the line.

(Kilbridge and Wester 1962)
The production cycle time is the fixed time separating the launching of two consecutive units. When the labor groups are linked by conveyor belts moving with uniform speed, the production cycle time is identical for all labor groups.

(Thomopoulos 1967)

Throughput time

The number of work stations multiplied by the cycle time gives the total time required for the assembly of the product.

(Kilbridge and Wester 1962)

Visually these terms can be shown as Fig 7.

![Fig 7. A system model of an assembly line in general with it's relevant terminology.](image)

2.2 Classification of assembly lines

The first and most distinctive difference between assembly lines is already explained in Chapter 1, i.e. the difference in model sequence (Fig 4). But of course there are a lot of other characteristics as well. These will be discussed in more detail now.

By far the best and most complete list of assembly line characteristics I have found in literature is the one by Boysen, Fliedner et al. (2007) (see Fig 8). They developed a classification scheme based on a widely accepted and successful classification scheme for machine scheduling (Graham, Lawler et al. 1979), using a three element tuple notation \([\alpha \mid \beta \mid \gamma]\), in which \(\alpha\) represents the precedence graph characteristics, \(\beta\) the station and line characteristics and \(\gamma\) the objectives used for designing the line (this will be discussed in chapter 3.3).
### Precedence Graph Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product specific precedence graphs:</td>
<td>$a_{ijk}$</td>
</tr>
<tr>
<td>$a_{ijk}$ = mix</td>
<td>Multi-model production</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Single-model production</td>
</tr>
<tr>
<td>Structure of the precedence graph:</td>
<td>$a_{ijk}$</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Precedence graph can have any acyclic structure</td>
</tr>
<tr>
<td>Processing times:</td>
<td>$a_{ijk}$</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Dynamic processing times (e.g., learning effects)</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Processing times are static and deterministic</td>
</tr>
<tr>
<td>Sequence-dependent task time increments:</td>
<td>$a_{ijk}$</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Caused by succession of tasks (tasks hinder each other)</td>
</tr>
<tr>
<td>Assignment restrictions:</td>
<td>$a_{ijk}$</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Incompatible tasks cannot be combined at a station</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Cumulative restriction of task-station-assignment</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Fixed tasks can only be assigned to a particular station</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Tasks may not be assigned to a particular station</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Tasks have to be assigned to a certain type of station</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Minimum distances between tasks have to be observed</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Maximum distances between tasks have to be observed</td>
</tr>
<tr>
<td>Processing alternatives:</td>
<td>$a_{ijk}$</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Processing times and costs are altered</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Precedence constraints are additionally altered</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Subgraphs: Subgraphs are additionally altered</td>
</tr>
<tr>
<td>$a_{ijk}$ =</td>
<td>Processing alternatives are not considered</td>
</tr>
</tbody>
</table>

### Station and Line Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement of workpieces:</td>
<td>$\beta_{ijk}$</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>(Average) work cost restricted by cycle time</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Each model must fulfill the cycle time</td>
</tr>
<tr>
<td>$\lambda_{ijk}$ =</td>
<td>Cycle time is obeyed with a given probability</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Single global cycle time</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Div: Local cycle times</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Unpaced line, with $x$ (g, sync)</td>
</tr>
<tr>
<td>$\lambda_{ijk}$ =</td>
<td>Asynchronous line</td>
</tr>
<tr>
<td>$\lambda_{ijk}$ =</td>
<td>Synchronous line</td>
</tr>
<tr>
<td>Line layout:</td>
<td>$\beta_{ijk}$</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>U-shaped line; with $x$ (g, n)</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>The line forms a single U</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Multiple U forming an n-U line</td>
</tr>
<tr>
<td>Parallelization:</td>
<td>$\beta_{ijk}$</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Parallel stations</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Parallel tasks</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Parallel working places within a station</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Neither type of parallelization is considered</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Maximum level of parallelization is unrestricted</td>
</tr>
<tr>
<td>Resource assignment:</td>
<td>$\beta_{ijk}$</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Equipment design problem; with $x$ (g, max)</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>If two tasks share a resource, investment costs are reduced at a station</td>
</tr>
<tr>
<td>$\lambda_{ijk}$ =</td>
<td>Most challenging task defines the needed qualification level of a resource</td>
</tr>
<tr>
<td>$\lambda_{ijk}$ =</td>
<td>Other type of synergy and/or dependency</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Processing alternatives are not considered</td>
</tr>
<tr>
<td>Station-dependent time increments:</td>
<td>$\beta_{ijk}$</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Station-dependent time increments are not regarded</td>
</tr>
<tr>
<td>Additional configuration aspects:</td>
<td>$\beta_{ijk}$</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Buffer lines are to be balanced simultaneously</td>
</tr>
<tr>
<td>$\beta_{ijk}$</td>
<td>Material boxes need to be positioned and dimensioned</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>Machines for position changes of workpieces</td>
</tr>
<tr>
<td>$\beta_{ijk}$ =</td>
<td>No additional aspects of line configuration are regarded</td>
</tr>
</tbody>
</table>

### Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{ijk}$</td>
<td>Minimize the number of stations $m$</td>
</tr>
<tr>
<td>$\gamma_{ijk}$</td>
<td>Minimize cycle time $c$</td>
</tr>
<tr>
<td>$\gamma_{ijk}$ =</td>
<td>Maximize line efficiency $E$</td>
</tr>
<tr>
<td>$\gamma_{ijk}$</td>
<td>Cost minimization</td>
</tr>
<tr>
<td>$\gamma_{ijk}$</td>
<td>Profit maximization</td>
</tr>
<tr>
<td>$\gamma_{ijk}$ =</td>
<td>Station times are to be smoothed; with $x$ (stat, line)</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Within a station (horizontal balancing)</td>
</tr>
<tr>
<td>$\lambda_{ijk}$</td>
<td>Between stations (vertical balancing)</td>
</tr>
<tr>
<td>$\gamma_{ijk}$ =</td>
<td>Only feasible solutions are searched for</td>
</tr>
</tbody>
</table>

Fig 8. The classification scheme for assembly line balancing (Boysen, Fliedner et al. 2007)
For now only some of the station and line characteristics will be considered.

- **Movement of workpiece**
  The line can move at a paced (cycle) time, or unpaced where each station has it’s own station time.

- **Line layout**
  The classic assembly line had all the workstation in a (serial) row. Nowadays also U-shaped assembly lines are used that are more compact and allow workers to work on 2 places on the “line” at the same time.

- **Parallelization**
  Assembly systems can have more than one parallel lines, stations or workplaces at a station.

- **Additional configuration aspects**
  Some assembly lines are equipped with additional aspects like buffer storages, feeder lines or workpiece orientation tools.

Another survey by Boysen et al. (Boysen, Fliedner et al. 2009) reveals some more characteristics about the stations and lines.

- **Station boundaries**
  Workstations can be designed in such a way that workers can cross the station boundaries if necessary, e.g. to temporary increase the station time. This can be at one or both sides (see Fig 9).

- **Concurrent work**
  Concurrent work enables the worker(s) of a stations to start processing although the previous station has not finished its work on the respective workpiece. This necessitates open stations as well as workpieces of an appropriate size, so that workers do not impede each other.

- **Homogeneity of stations**
  In practical cases, an assembly line may consist of stations with diverging characteristics. For instance, open and closed stations can be mixed throughout the line.

- **Launching disciplines**
  The interval at which workpieces are launched down the line can either be fixed or variable.
2.3 Assumptions

Most research papers, like the ones from Boysen et al., make the following assumptions related to the physical assembly lines:

- There are no buffers between stations. Thus, the production sequence is determined prior to the launch such that a reordering or preemption of jobs is impossible.
- The workpieces have a fixed location on the transportation system, only their orientation may change.
- The model-mix, i.e. the demand for models throughout the planning horizon, is known with certainty and not subject to changes (static problem), so that there are no rush orders.
- Multiple models contain different materials and require different tasks with individual processing times, such that the demands for material and the utilization of the stations’ capacities may change from model to model.
- It is supposed that there are no disturbances, like machine breakdowns or material stock-outs, so that a re-sequencing is not considered.

This report will obey these same assumptions, unless stated otherwise.
3. What are the challenges in designing assembly lines?

This chapter describes the basic concepts that are applicable to all assembly line design problems, no matter what they look like. First the difficulties that occur in operating and designing assembly lines will be defined. After that a general design methodology will show how to minimize these difficulties. The last part will give an outline of the objectives by which this can be done.

3.1 Difficulties

As stated in the previous chapter, any assembly line consists of a sequence of work stations where particular tasks are being done by (an) operator(s). Workpieces move automatically from one station to another at a given cycle time. How to assign the tasks (and operators) to workstations and how to determine the cycle time are the main questions.

Consider a simple case with a continuous flow line and closed work stations. If the work that has to be done at an assembly station would take longer than the cycle time, the workpiece won’t be able to leave this station (yet). This is called blocking. When the station next to it did already finish its work, but now needs to wait because there is no new workpiece coming, it is called starvation (Dallery and Gershwin 1992).

Other difficulties that can occur in designing assembly systems are constraints like limited floor space, limited number of operators, zoning constraints (like painting can only be done in a designated area), or the decisions to automate certain tasks by machines or not.

How to cope with these difficulties is shown in the next part.

3.2 Basic design methodology

The first and most essential step in designing every assembly line is to assign the tasks to workstations. Basically this consists of grouping the tasks in a particular way that balances the workload as evenly as possible over a number of operators/workstations. This is called load balancing. In the optimal solution, all stations do the same amount of work and no blocking or starvation will occur (i.e. 100% utilization or line efficiency).

**Load balancing**

Load- (or line-) balancing can be defined as follows.

*The line-balancing problem is to apportion the total assembly work among the stations or operators on the line as evenly and compactly as possible. This is to be done while heeding given restrictions on the order in which work may be performed, and without exceeding the chosen cycle time at any station.*

(Kilbridge and Wester 1962)

*Line balancing is a procedure of assigning work to assembly operators in such a manner as to balance the work assignments among the operators and to minimize the number of operators required.*

(Thomopoulos 1967)
Manufacturing a product on an assembly line requires partitioning the total amount of work into a set \( V = \{ 1, \ldots, n \} \) of elementary operations named tasks. Performing a task \( j \) takes a task time \( t_j \) and requires certain equipment of machines and/or skills of workers. The total workload necessary for assembling a workpiece is measured by the sum of task times \( t_{\text{SUM}} \). Due to technological and organizational conditions precedence constraints between the tasks have to be observed. Any type of assembly line balancing problem (ALBP) consists in finding a feasible line balance, i.e., an assignment of each task to a station such that the precedence constraints (Fig. 1) and further restrictions are fulfilled. The set \( S_k \) of tasks assigned to a station \( k ( = 1, \ldots, m) \) constitutes its station load or work content, the cumulated task time \( t(S_k) \) is called station time.

(Boysen, Fiedner et al. 2008)

**Precedence diagram**
All definitions talk about satisfying the precedence relations. This means that there is a particular way to assemble the product, i.e. the product has to be assembled in a particular sequence. For example, a bottle can’t be filled when the cap is already on.

A common way to visualize this assembly sequence is by use of a precedence diagram, first developed by Salveson (1955). Fig 10 gives an example of a precedence diagram. The numbers inside the circles identify the various elements of work and the numbers outside the circles refer to the corresponding time durations. The arrows indicate precedence relations. Thus, element 1 of duration 9 must precede element 3 of duration 10, and element 7 of duration 13. Element 3 must precede element 5 of duration 17 and element 7 must precede element 14 of duration 22, and so forth.

![Fig 10. Illustrative assembly precedence diagram. (Kilbridge and Wester 1962)](image)

**Solution approaches**
As you can imagine the optimum of zero starvation and zero blocking (equal station times) is usually hard to reach in practical applications, where there are a lot of different tasks with different task times (Buxey, Slack et al. 1973).
There are several ways to cope with this. The easiest and most common one is to allow starvation, keeping the line flowing with a cycle time equal to the longest station time. This will cause idle time at some other stations and thus will decrease the line efficiency, but it works.

Some special rescue options exist however, for when the station time exceeds the cycle time (Wild 1972):

- The whole assembly line is stopped until all stations have finished work on their current workpiece,
- Utility workers support the operator(s) of the station to finish work just before the station’s border is reached,
- The unfinished tasks and all successors are left out and executed off-line in special finishing stations after the workpiece has left the last station of the line, or
- The production speed is accelerated at the risk of quality defects.

Because these options are considered to be more costly and complicated, they aren’t used much. They are out of scope for almost every research paper, so also for this one.

Salveson is known to be the first one to have published an analytical method to solve the line balancing problem as efficient as possible (Salveson 1955). After that lots of other methods followed, like the heuristic Ranked positional weight technique (Helgeson and Birnie 1961).

In recent years, (Boysen, Fliedner et al. 2007) did a great effort by listing all these papers, and classify them according to the classifications scheme already shown in Chapter 2. A snippet of their list is shown in Fig 11. In total about 150 papers are indexed. Besides this review, Kilbridge and Wester (1962), Baybars (1986) and Ghosh and Gagnon (1989) also listed the related papers until the time they were written. All of these are recommended readings.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Notation</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bukchin et al. (1997), Bukchin and Masin (2004)</td>
<td>$[\text{line} \mid \text{work} \mid \text{m, score}]$</td>
<td>B, B&amp;B</td>
</tr>
<tr>
<td>Bukchin et al. (2002)</td>
<td>$[\text{mix} \mid \text{ptask} \mid \text{score}]$</td>
<td>M, HS, HI</td>
</tr>
<tr>
<td>Buxey (1974)</td>
<td>$[\Delta \text{fib}, \text{link}, \text{inc}, \text{max} \mid \text{pstat} \mid \text{score}]$</td>
<td>HS</td>
</tr>
<tr>
<td>Capacho and Pastor (2004)</td>
<td>$[\text{path} \mid \text{score}]$</td>
<td>M</td>
</tr>
<tr>
<td>Carnahan et al. (2001)</td>
<td>$[\text{sum} \mid \text{c, score}]$</td>
<td>HS, GA</td>
</tr>
<tr>
<td>Carraway (1989)</td>
<td>$[r^\text{step} \mid \text{prob} \mid \text{m}]$</td>
<td>DP</td>
</tr>
<tr>
<td>Carter and Silverman (1984)</td>
<td>$[r^\text{job} \mid \text{Co}]$</td>
<td>HS</td>
</tr>
<tr>
<td>Chakravarty (1988)</td>
<td>$[r^\text{job} \mid \text{E}]$</td>
<td>HS, DP</td>
</tr>
<tr>
<td>Chakravarty and Shtub (1985)</td>
<td>$[\text{mult} \mid \text{div} \mid \text{Co}]$</td>
<td>M, HS</td>
</tr>
<tr>
<td>Chakravarty and Shtub (1986)</td>
<td>$[\text{mult, r}^\text{ext} \mid \text{div} \mid \text{Co}]$</td>
<td>HS</td>
</tr>
<tr>
<td>Chiang and Urban (2002)</td>
<td>$[r^\text{job} \mid \text{prob} \mid \text{m}]$</td>
<td>HS, HI</td>
</tr>
<tr>
<td>Dar-El and Rabinovitch (1988)</td>
<td>$[\text{mult, r}^\text{opt} \mid \text{Co}]$</td>
<td>M</td>
</tr>
</tbody>
</table>

Fig 11. A snippet from the research index on load balancing by Boysen et al. (Boysen, Fliedner et al. 2007).
The classification scheme by Boysen et al. lists some interesting characteristics that define the balancing problem, called precedence graph characteristics. One of them is how the processing times are interpreted. Manual labour is often subjected to stochastic deviations, as the performance of human workers depends on a variety of factors, like motivation, work environment or the mental and physical stress (Tempelmeier 2003), where robot assembly is assumed to have a deterministic processing time. On the other hand, human workers are know to be able to do a task faster after some times, called the learning effect (Thomopoulos and Lehman 1969), that implies dynamic decreasing processing times.

Other factors are the rules of assigning specific tasks to specific workstations (or not) and the question if small sequence-dependent time increments like tool change time are considered.

3.3 Design objectives

One of the first papers on line balancing (Kilbridge and Wester 1962) states three possible goals for designing an assembly line:

- Minimize the number of operators
- Minimize the cycle time
- Minimize the balance delay, which is defined as the amount of idle time on the line caused by the uneven division of work among operators or stations.

Boysen, Fliedner, et al. (2007) extended this list to:

- Minimize the number of stations
- Minimize the cycle time
- Maximize the line efficiency
- Minimize the costs
- Maximize the profit
- Smoothen the station times (horizontal/vertical balancing)
- Other related objective
- No objective function, only feasibility

Following all these possible objectives, Bukchin (1998) examined the quality of five performance measures used with mixed model assembly lines. One of the five was found to be significantly better than the others, and showed superior performance for relatively short assembly lines. The following performance measures were considered in the study:

1. Smoothed Station measure (Thomopoulos 1970)
2. Minimum Idle Time measure (Macaskill 1972)
3. Station Coefficient of Variation measure (Fremerey, 1991)
4. Model Variability measure (Bukchin 1998)
5. Bottleneck measure (Bukchin 1998)

Extensive simulation experiments indicated that the Bottleneck measure outperformed the other measures in showing a high significant correlation with the operational objective, the throughput (see Fig 12).

The ‘Bottleneck’ measure is a performance measure of the line cycle time, which is the inverse of the line throughput. It is obtained by estimating the expected value of the assembly time at the
The expected value is attained by summing the products of the probability of each model assembled at each station to be the largest station time with the model assembly time.

Fig 12. Outcome of performance measure simulations (Bukchin 1998).
4. How to design mixed-model assembly lines?

All of the previous concepts are applicable for any assembly line design problem. However, from now on we will focus on the mixed-model assembly line, so $\alpha_i = \text{mix}$ according to the Boysen classification (Fig 8).

While mixed-model assembly line design is much more complicated than single model assembly line design, it also has the advantage that more parameters can be influenced to meet the particular objective. The most common parameter is the sequence of the models that are launched into the line. The first part of this chapter will describe this.

After that, this chapter will show some of the most interesting methodologies found in literature on designing mixed-model assembly lines, using the basics from the previous chapter.

4.1 Model sequencing

Where load balancing applies to all types of assembly lines, model sequencing is only relevant to mixed-model assembly lines where there are different models on one line to be mixed. The first research paper on this topic was published in 1964 (Wester and Kilbridge 1964).

In literature the following formulations on model sequencing can be found.

*The objective of the sequencing procedure is to determine the ordering in the flow of models which allows the optimum utilization of the assembly line operators.*

(Thomopoulos 1967)

*The main emphasis in model sequencing is placed on finding a product sequence that minimizes idle time while conforming to the required product mix. Ideally a model which overloads a station should always be followed by one which allows slack time there, but this is difficult to achieve in practice.*

(Buxey, Slack et al. 1973)

*In addition to the long- to mid-term assembly line balancing problem, mixed-model assembly lines give rise to a short-term sequencing problem, which has to decide on the production sequence of a given number of model copies within the planning horizon, e.g., one day or shift. Although (almost) any intermixed sequence of models is technically feasible, its significant economic impacts necessitate a thorough planning. In particular the labor utilization at workstations and the spreading of material demand are determined by the model sequence and are, hence, in the center of two different general objectives.*

(Boysen, Fliedner et al. 2009)

Following from the last definition by Boysen, Fliedner et al., modern model sequencing can be done to comply with two general objectives: to prevent work overload or to meet Just-in-Time material demand objectives.

*Preventing work overload* is the most common one. On mixed-model assembly lines, the precedence diagrams of the models will be similar, but tasks times will differ every now and then (some will be 0). If the stations can somehow be made to cope with flexible station times, and a model mix can be defined that on average the station times will be more equal, the line will be more balanced. Simply
speaking; if you first assemble a difficult workpiece with a long assembly time, which is followed by a simple workpiece with a short assembly time, on average the station time will be somewhere in between, and thus faster than the max cycle time of either of these.

The Just-In-Time material demand objective approaches it from another view. Different models are composed of different product options and thus require different materials and parts as input, so that the model sequence influences the progression of material demands over time. An important prerequisite for JIT-supply is a steady demand rate of material over time, as otherwise the advantages of JIT are sapped by enlarged safety stocks that become necessary to avoid stock-outs during demand peaks. That’s why the right sequence of models launched on the line can help smoothen the material demand. This new approach has gained attention since the 1990s.

Bard, Dar-EI, et al. (1992) were the first ones to develop a basic classification scheme for the sequencing problem (Fig 13)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch discipline</td>
<td>Fixed, variable (single or multi-valued)</td>
</tr>
<tr>
<td>Line movement</td>
<td>Synchronous (paced or indexed), asynchronous</td>
</tr>
<tr>
<td>Station restrictions</td>
<td>Open, closed (any combination)</td>
</tr>
<tr>
<td>Operator schedule</td>
<td>Early start, late start</td>
</tr>
<tr>
<td>Design objective</td>
<td>minimize line length, minimize throughput time</td>
</tr>
</tbody>
</table>

Fig 13. Characteristics of the sequencing problem (Bard, Dar-EI et al. 1992).

More recently, Boysen, Fliedner et al. made a more advanced classification scheme for the research done on model sequencing (Boysen, Fliedner et al. 2009), in a same way as the load balancing classification. Their classification considers the three different cases: mixed-model sequencing, car sequencing (which is a more rough, rule based approach for avoiding work overload) and level scheduling, together with the combined hybrid version. Again a small snippet of their index is given in Fig 14.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Notation</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bard et al. (1992)</td>
<td>open, var[PM] [j] or [j1], open, var[PM] [j1] or [j]</td>
<td>M</td>
</tr>
<tr>
<td>Bolet (1997)</td>
<td>[j]</td>
<td>M, B, HM</td>
</tr>
<tr>
<td>Bolet and Yano (1992a)</td>
<td>[1 1]</td>
<td>M, P, HS</td>
</tr>
<tr>
<td>Bolet and Yano (1992b)</td>
<td>[1 1]</td>
<td>P</td>
</tr>
<tr>
<td>Bolet et al. (1994)</td>
<td>setup ([wo, Co(*)])</td>
<td>M, B, E, HS</td>
</tr>
<tr>
<td>Boysen (2005)</td>
<td>setup ([wo, Co(*)])</td>
<td>M, P, HM</td>
</tr>
</tbody>
</table>

Fig 14. A snippet of the research index on model sequencing by Boysen et al. (Boysen, Fliedner et al. 2009).
4.2 The combined balancing-sequencing problem

As made clear by now, the efficient utilization of a mixed-model assembly line requires the solution of two separate but related problems: the division of work between workstations/operators and the sequencing of models on the line.

The basic idea of designing a complete mixed-model assembly line, can best be shown visually using Fig 15. This flow chart shows that the first step is to define the expected model mix, i.e. what models are to be assembled and in which quantities? This leads to a virtual average model. The way the virtual average model is constructed obviously influences the balancing results, depending on the objective function used (Thomopoulos 1970; Van Zante-De Fokkert and De Kok 1997). Normally it is done by simply combining the individual precedence diagrams using weighted average task times (Fig 16). According to this model the assembly line can then be designed by balancing, as described before. Once this is done the line can be build, and the long term decisions have been made.

To get the best performance as possible now, the model mix has to be controlled in such a way that it approaches the virtual average model as close as possible, so the balancing is valid. Because the actual demand can differ from the forecasted demand (where the average model is based on) from day to day, the model sequencing is a short term problem and is often defined per day or even per work shift.

This shows the difference between the two problems. Where load balancing is a rough long term decision that is normally done only once in a while, model sequencing is a subtle short term control problem that can help get the best out of a line but requires more precision.

![Flow chart for balancing-sequencing a mixed model assembly line](Fig 15)
Fig 16. A combined precedence diagram composed of two different models (Van Zante-De Fokkert and De Kok 1997).
Fig 17. An overview of the most important publications and other milestones.
4.3 Design methodologies

Numerous mixed-model assembly line design methodologies are developed during the years. Some are very similar, others unique. The most interesting (and most cited) ones will be introduced now. Fig 17 also shows them together with some other milestones on a timeline.

**Line Balancing-Sequencing for Mixed-Model Assembly (Thomopoulos 1967)**
This is one of the first publications on mixed-model sequencing, and is classified by Boysen et al. as \( \text{[open]Co(wo;idle)} \), meaning that it considers open station boundaries and its goal is to minimize the costs of idle time. The virtual average model used is a weighted combined precedence graph. The sequencing procedure is based on the computation of penalty costs of inefficiencies (idleness, work deficiency, utility work, work congestion) resulting from sequencing the various models. The entire calculation is included in the paper.

**Production-Line Balances for Mixed-Model Lines. (Macaskill 1972)**
This paper describes the development of the first computer simulation of mixed-model assembly line balancing and sequencing, based on the previous paper by Thomopoulos. Rated as \( \text{[mix]E} \), it optimizes the line efficiency. At that time, the program was written in FORTRAN and run on a CDC 6400 computer, so calculation speed and memory usage were real issues.

**Assembly line balancing with processing alternatives: an application (Pinto, Dannenbring et al. 1983)**
Where all previous publications assumed that there is only one way to assemble the product (i.e. one precedence diagram and one worker per work station.), this paper includes other processing alternatives. This includes alternative assembly sequences, but also the choice of automating particular segments of the line, so multiple tasks can be done at once or tasks can be done faster: Fig 18 shows how it can change the precedence diagram. However, if this doesn’t help the balancing of the line to improve, it doesn’t lower the operating costs. Accordingly, this paper is indexed as: \( \text{[pal]Co} \). It also includes an illustrative industrial application.

![Fig 18. An example precedence diagram with processing alternatives (Pinto, Dannenbring et al. 1983).](image)

**Team-oriented assembly system design: A new approach (Bukchin, Darel et al. 1997)**
A new design methodology for team-based assembly systems is presented in this paper. Team-oriented assembly (TOA) systems support the objectives of modern assembly systems, while creating a more satisfactory working environment. This means parallel work is at one station ( \( \text{[pwork]m, score} \) ). This principle of course reduces the number of stations, and is said to...
increase flexibility, product quality and throughput. The two stage approach, macro and micro, first
defines teams by looking at the product structure and it’s Bill-Of-Materials (i.e. per sub-assembly),
before balancing the smaller sub-assembly lines per team.

**Balancing and sequencing manual mixed-model assembly lines (Merengo, Nava et al. 1999)**

Merengo et al. developed an extensive algorithm for balancing and sequencing mixed-model assembly
lines as smooth as possible, in order to minimize the number of workstations and the number of
incomplete units. This is done using an extra horizontal balancing step, which minimizes the variation in
station times (see Fig 19 on the vertical axis) so they will never exceed the cycle time.

\[ \text{\textit{mixed}, SSL_{line}, SSL_{stat}} \]

![Fig 19. Combined impact of horizontal balancing and sequencing on the generation of incomplete units (Merengo, Nava et al. 1999).](image)

**Efficient algorithms for buffer space allocation (Gershwin and Schor 2000)**

Where most other research focus is on the ideal line without any buffer spaces in between the line,
this paper develops an efficient algorithm for buffer space allocation. They state that in particular cases
buffers are necessary to increase the average production rate of the line. This is especially true when
machine failures or variable processing times are considered. If the buffers are too large though, the
work-in-process inventory and capital costs of the buffer location will outweigh the benefit of
increased productivity. If buffers are too small, the machines will be underutilized or demand will not be met. So, it is essential to determine buffer sizes to achieve the desired performance.

This can be done in two different ways. The goal of the primal approach is to minimize the total buffer space required for the line to meet a given average production rate. The goal of the dual approach is to maximize the production rate achievable with a given total buffer space. These algorithms are described and example calculations are given.

Battini, Faccio et al. (2008) also describe the dual approach, and illustrates it with a simulation research.

**Design rules for implementing the Toyota Production System (Black 2007)**

Still being one of the leading companies in efficient assembly, this paper describes how the Toyota Production Systems works. It discusses four design rules that define the TPS.

The first design rule describes that all production processes operate according to the daily demand, in whatever mix the downstream customer requires.

The second design rule covers the one-piece flow that is realized by the use of U-shaped assembly lines (Fig 20). Many of these sub-assembly lines operate in synchronization with the final assembly line.

The third design rule states that each workstation’s processing time is less than the necessary takt time to provide a margin of safety for the suppliers to final assembly.

The fourth design rule covers the production and inventory control system, a pull system known as Kanban.

---

**Fig 20.** The traditional linear subassembly line, using conveyors, is redesigned into a U-shaped cell using walking operators (Black 2007).

The outcome is that the TPS contains a network of linked U-shaped sub-assembly cells. It then gives a guideline on how to implement Lean into a company.
A team-oriented design methodology for mixed model assembly systems (Cevikcan, Durmusoglu et al. 2009)

Recently Cevickan et al. integrated the team oriented assembly approach by Bukchin et al. with the time smoothening by Merengo et al. This leads to a methodology best described by Fig 21.

They furthermore developed software coded with MATLAB and show it’s use in an industrial application.

![Fig 21. The proposed methodology and it’s inputs and outputs (Cevikcan, Durmusoglu et al. 2009).](image-url)
4.4 Software

In 1965 the first publicly available computer program was written to solve the simple load balancing problem: COMSOAL (Arcus 1965). The research performed in the 70s and 80s almost exclusively focused on the development of exact methods to solve larger instances of this basic assembly line problem. FABLE (Johnson 1988) was, and still is the best-performing exact algorithm to do so (Lapierre and Ruiz 2004). But because of the difference in problem types, often custom optimization software has to be developed. This can be done using standard programming languages like C++ or MATLAB. The only known modern assembly line design software is OptiLine (http://www.optimaldesign.com/OptiLine/OptiLine.htm).

On the other hand, new or existing assembly lines are often simulated to predict their behavior. This can also be done using custom programs, made using Delphi/TOMAS (Veeke and Ottjes 2000) for example. But some graphical simulation packages exist as well. Examples are Siemens Tecnomatix Plant Simulation (http://www.plm.automation.siemens.com/), Simul8 (http://www.simul8.com/) and Dessault Systemes Delmia (http://www.3ds.com/products/delmia). However, users have to remember that simulation is not a design or optimization tool.
5. Mixed-model assembly lines in the real world

This chapter describes assembly lines in the real world. This is first done according to what is written in literature about the research work published. This introduces a remarkable statement. Furthermore, this chapter will describe some basic observation made during three company visits in Japan.

5.1 Gap between current state and research

The literature review on load balancing by Boysen, Fliedner et al. (2007) concludes that a lot of scientific effort has been made in the past, but that it’s not clear which research paper describes which variant of the problem. That’s why they think companies don’t use these analytical methods, and so there is still a large gap between the industry and science. Following their unified literature review, they reveal a number of important open fields of research which require in-depth discussion to narrow the gap between research and practice, at that time (Boysen, Fliedner et al. 2007). These fields are:

- **Rebalancing**
  Due to shifts in demand structure or introduction of new product variants, assembly lines are more often rebalanced than designed from scratch. Most papers only consider new designs, with less “historical” constraints.

- **Cost synergies**
  Costs are often assigned to tasks or stations, but when several tasks require the same resource and can be assigned to the same station, cost should better be assigned to resources.

- **Feeder lines**
  Real world assembly often have one or more feeder lines that have to be balanced with the main line as well.

- **Material supply**
  Almost completely ignored in literature, assembly line stations also need to be supplied with materials. These also need to be balanced with the assembly line somehow.

- **Parallel working places**
  Sufficiently large workpieces give the ability to perform operations at different mounting places of a product at the same time. The station time can no longer be computed by simply summing up the task times, but requires the solution of a detailed scheduling problem instead.

- **Processing alternatives**
  Most tasks can be performed in different ways causing the precedence diagram to change resulting in different balances and costs (as explained in Chapter 4.3 by Pinto, Dannenberg et al., which is one of the few papers on this topic).

- **Disassembly line balancing**
  Though a lot of characteristics are the same in assembly and disassembly, one major aspect is different. Where one finished product leaves an assembly line each cycle, a disassembly line outputs all consisting parts that consequently have to be taken somewhere. This is like the inverse of the “material supply” problem mentioned before. No sufficient papers have been written on this topic.

- **Test beds and flexible solution procedures**
  To conclude, the survey revealed that there is a need for realistic evaluation of all solution models, to ultimately be able to develop a solution algorithm flexible enough to jointly cover as many problem characteristics as possible.
Their research on model sequencing (Boysen, Fliedner et al. 2009) revealed some other research needs as well:

- Stochastic task times hardly ever been considered
- U-shaped assembly lines and feeder lines have hardly been considered in literature, but do exist in many industries
- Only a few approaches consider diverging station characteristics, in other words: a mix of open, closed and/or parallel workstations
- The relationship between work overload and material aspect has hardly been studied
- The effect of the different objectives on the company’s general objective of profit maximization isn’t known

Furthermore, they state that more empirical research has to be done to evaluate all of the approaches for real-world applications, to provide more insight into this complex matter.

Another publication completely dedicated to line balancing in the real world (Falkenauer 2005) confirms the gaps by Boysen et al. It also adds the fact workstations can often not be moved around or eliminated that easy. Furthermore it points out different ergonomic constraints related to the workstations and work load. It concludes with the fact that only one software package is capable of handling all this complexity, OptiLine, but it looks like the author is biased since it is his own product.

On the other hand, companies do run mixed-model assembly lines dealing with most of the previous features. So how do they do that? The answer is most of the times simple: industrial planners often think that an optimal flow line design can be developed based on the experience they have acquired with similar past projects (Tempelmeier 2003). In many cases, planners have only limited knowledge about the existence of practically applicable evaluation methods. But we now know that even a small change of system characteristics may generate a considerably different behavior of the system, especially considering the total line balance that makes every line unique. Therefore, tools are required that can provide system-specific performance measures in a fast and reliable manner.

This said, it is obvious that research and industry will have to help each other to be able to ultimately reach the optimum solution as illustrated in Fig 22.

![Fig 22. An impression of the status of assembly in the real world and research, vs the optimum.](image-url)
5.2 Observations during company visits

To complement this research I have had the chance to see three factories in Japan to visualize and verify everything I’ve read. The three companies all had different profiles. One was a sheet metal parts manufacturing plant, the other a rough assembly line of excavators and the third one was a highly advanced air conditioner factory (see Fig 23).

![Fig 23. Visited company profiles.](image)

At the part manufacturing plant it could easily be seen that it operated as a multi-model line, with the obvious reason that changing the stamping dies took so long that one-piece flow was impossible. It was also true that this methodology caused quite a lot of buffer space throughout the plant.

The excavator assembly was done as expected by the use of parallel work, because the large size of the workpiece made this possible, and thus would decrease the number of stations needed. The size also implied a long throughput time, and so a slow cycle time. The model sequence was mixed.

The air conditioner plant was the most impressive one. It could be seen that their production system was inspired by the Toyota Production System, including everything related to JIT and Lean. A lot of the production was done in-house, and everything seemed to be very well balanced with the final assembly line. Even the part supply to the workstations was balanced and done automatically by use of AGV’s (Automatic Guided Vehicles).

An interesting observation was that at one point one of the final assembly lines was split up in two. The regular models continued on a continuous flow line, but the most complex (low volume, high variety) ones went to a special assembly cell. This cell consisted of a number of workstations where an entire model was assembled by one worker, so no assembly line anymore (Fig 24). Somehow this was needed to cope with the variety, and they say it significantly decreased the throughput time for these models. It is interesting though, because it’s actually back to the craftsmen, but then in a streamlined way. I could not find much about this theory in literature.
Fig 24. A model of the assembly cell used at Daikin.
Conclusions

The main objective of this report was to make clear how mixed-model assembly lines are designed and operated. In order to do so, first all the basics related to assembly lines have been discussed. This made clear that the first step in designing any assembly line is to assign assembly tasks to workstations and workers. This process is called load balancing, and determines the layout of the line.

In case of a mixed-model assembly line, i.e. an assembly line where multiple similar products are being assembled in a one-piece mixed sequence, another important question has to be answered: the order in which the models are launched down the line. This can have a major impact on the performance of the line.

To illustrate these general ideas, a number of design methodologies are explained in this report. Each methodology covers a particular area of the problem, because up until now there is no real general approach available.

It is obvious that assembly line design has been, and still is, an active field of research. With more than 300 publications it is one of the main topics in operations management and production research. However, most of the research is done in such a limited way that it is hard for practitioners to use these theories in real-world applications. Also, most of the theories haven’t even been confirmed by empirical studies.

So it can be concluded that at the moment there is no optimal solution for designing a mixed-model assembly line. What is written in scientific literature is too limited, and what is done in industrial practice is not based on optimization methods but on experience.

In recent years, researchers like Nils Boysen, Malte Fliedner, Armin Scholl and Christian Becker (all from Germany) picked this problem up by categorizing all publications according to one unified classification scheme. This way clarifies what is done in the past, and what still has to be done in the future. It also makes the publications easier to find for the practitioners. Nowadays their open archive can be found at http://www.assembly-line-balancing.de/. This is of great importance to bring science and business closer together, to ultimately be able to design the optimal assembly system. This design methodology should of course include load balancing and model sequencing, but also processing alternatives, flexible station and line characteristics and parallel and team working.
Final words

I would like to thank Prof Fujita for letting me stay in his laboratory at Osaka University.

Furthermore I would like to thank Prof Fujita for arranging the company visits, which were a valuable resource for my work.

All of this was made possible by the IGM exchange program of Prof Tomiyama, which I’m also very thankful for.

Being at the other side of the world really opened my eyes in a lot of ways, not only scientifically, but also in a social and cultural way.

It was a time I won’t forget.

That’s all.
Thanks for reading.

いじょうです
ありがとうございました。
Bibliography


Appendix

The following parts are background information only.

Appendix I. Research method

The aim of this research assignment was to acquire knowledge on a certain subject related to Production Engineering and Logistics. By searching for information, e.g. in books, journals, conference proceedings, brochures, on the internet and if necessary by interviews, the student learns how to gather information/data on a subject.

The main source of information for this research were publications from journals on operations and production research. These were all found using Scopus (http://www.scopus.com/), integrated in a paper management software program simply called Papers (http://www.mekentosj.com). This eventually lead to a database filled with 76 relevant papers (Fig A1).

![Fig A1. A screenshot of Papers, a software program to find, read and manage papers.](image)

Having tagged all the papers with keywords and notes during reading, I build up a very useful, and easily searchable data source for this report.

Also during reading I’ve build a mind map to put everything into perspective (Fig A2). This is a useful way to categorize and visualize the relations between the different terms and methodologies the papers described.
I started reading the oldest papers first at the start of my research, assuming that these would be most basic and thus easy to understand. This appeared to be different however, because most old papers only describe mathematical methods for small parts of the problem in a very abstract way. So I continued searching for more recent papers that explained the entire problem in an easier way. I then found a couple of review papers that then became the guide for this report. Since hundreds of papers have been written on this subject these review papers helped me a lot.

All referred papers in this report are read (or at least scanned), except for the oldest ones I couldn’t get access to:


Overall this research took about four months, of which one was for orientation, two for reading and another one for writing.
Appendix II Company visits
This appendix will give the raw reports of the three company visits I did during my stay in Japan.
The observations from these visits are discussed in more detail in chapter 5.

Kokusan
Date: May 12th 2009, 15:00-17:00
Location: Kyoto plant, Ayabe, Kyoto prefecture, Japan

About Kokusan
The visit started with a general presentation about Kokusan. It was established in 1950, and the current Kyoto plant opened on May 10th 1998. It’s about 20,000 square meters big, and employs 56 workers. It’s main business is the design and manufacture of automotive gasket parts including Cylinder Head Gaskets, Exhaust Manifold Covers (Heat Shields), various Metal & Soft Gaskets, Valve Body Separating Plates, Formed Wire Mesh Parts, Thrust Metals, etc. An illustration of these product is given in Fig A3. The main customers are Mitsubishi, Mazda, Daihatsu and Isuzu.

![Fig A3. The product that Kokusan make.](image)

As you can see most parts consist of formed metal plates, except for the formed wire mesh parts.

For more info please refer to [http://www.kbk-k.co.jp/](http://www.kbk-k.co.jp/)
Factory tour
Here are some of the observations I made by walking around in the factory. Unfortunately I couldn’t completely understand everything because of language difficulties.

The main process of the factory consists of presses for fabricating the metal plates. A systematic view of the process for producing the heat insulator is shown in FigA4 (this is the only process we’ve seen). The different parts of the process are divided into the work done in each work station. It has to be noted that not all parts pass all stations.

On average they make 10 batches of different models a day, which requires the stamping dies to change every time. These dies come from an automated warehouse, on the side of the building. A tool change usually takes 20 to 30 minutes. The total output of products is about 200,000 parts/month.

On the second floor of the building the production of the mesh parts takes place, by knitting metal wires. This is done by 15 machines producing different sized meshes. Next to it are two machines to cut the long strokes of meshes into shorter pieces, and two machines to press these meshes into rings so they can be used as seals that absorb vibrations and heat. All of these machines are operated by only a couple of workers.

Observations
Because of the continuously changing requirements (demand) from the car manufacturers, Kokusan has to deal with a lot of variety in their production. This causes them to have lots of stamping dies, which take up a lot of space. It also means that a lot of R&D has to be done each time to design the part and the tooling, which is sometimes also produced by themselves. After that they also have to test the prototypes using their own stress tests. This means the range of their “core business” is quite wide. Besides that, the variation causes a lot of batch changes a day, which consume about 10 times 25 minutes, which is around half of the day! Furthermore, they have a lot of Work In Progress, because all
different product have different cycle-times, so the “line” doesn’t really flow. The assignment of the project group of Professor Fujita is therefore to design the products more as a family, so they can share parts and thus tooling, which would decrease the batch change time a lot.
Daikin
Date: June 30th 2009, 13:00-16:00
Location: Shiga plant,
Kusatsu, Shiga prefecture, Japan

About Daikin
Daikin is a global company that is mostly know for manufacturing air
conditioners. It was founded in 1924, and nowadays employs about
36,000 people worldwide. Besides the air conditioning division (which
generates 88% of the total sales) it also has chemical, electronics, oil
hydraulics and defense deviions. The total sales in 2007 reach up to 1.3 trillion Yen (8.3 billion Euro).

The Shiga plant I’ve visited (Fig A5) is part of the Air Conditioning Division. Besides a lot of
production, also most of the R&D is done here.

Fig A5. An overview of the Daikin plant in Shiga.

The plant consist of 3 main factories. I’ve visited Factory 1 (nr5) which makes the outdoor units of
consumer air conditioners, and Factory 2 (nr6) where the indoor units are made.

Because of the season-dependent sales, the factory has to cope with quite some variation. Their
solution to this is a very advanced mixed-model assembly system which they call the Daikin PDS
production system. This system is inspired by and developed in corporation with the engineers of
Toyota.
As you can see, they once started as a (multi-model) lot production system. The amount of stock back then was enough for 1 month. As the demand raised, the production had to become more efficient. That's why the mixed-model production system was introduced in 1978, reducing the stock to 2 weeks. From 1999 and on, their own developed so called PDS “high cycle” production system reduced this even more to less than 3 days.

**Factory tour**

Once inside the factory you can directly see a lot of work has been done on making the production as efficient as possible. Products flow smoothly on the lines, and most of the parts are supplied automatically by AGVs from the warehouses to the workstations, as shown in Fig A7.

It is a true mixed-model assembly line, where different models follow each other in a random (probably well defined) sequence, with multiple points where the right sub-assembly has to meet the right custom parts. The information infrastructure behind this has to be very advanced!

**Observations**

To achieve the flexibility in the model mix, some different things are done, as far as I have seen. On the outdoor unit assembly line, the workstations are completely open, so that the length and thus
the time are flexible. Apparently the model mix is defined in such a way on average this is sufficient enough.

On the indoor unit assembly line, the most difficult models (with high varying assembly times) are directed to an assembly cell. This consists of 10 workstations with 7 workers that assemble the entire product by themselves, and then move on to one of the other empty stations where the next parts are waiting to be assembled (Fig A8). All the supply of materials is automated, and even the height of the work table is adjusted automatically to the workers' length. All assembly times are measured and the cycle time is set to the average. Displays show the target of the day, including sub-targets at smaller time intervals versus the current number of finished products. If the target isn’t reached for the day, workers simply have to continue working.

![Diagram](image)

Fig A8. A model of the cell assembly used at Daikin. A control system measures the available workstations and workers, to assign them to a workpiece with components.
Komatsu
Date: June 1st 2009, 14:00-17:00
Location: Osaka plant,
Hirakata, Osaka prefecture, Japan

About Komatsu
Komatsu’s main business is the manufacturing of construction and mining equipment, utilities and industrial machinery. It was founded in 1921, and currently employs almost 40,000 people worldwide. It’s consolidated sales reach up to 2 trillion Yen, which is about 15 billion Euro.

The Osaka plant I’ve visited started in 1952, and is now the main location for the production of large and medium-sized hydraulic excavators, large bulldozers and mobile crushers (Fig A9).

Fig A9. A Komatsu excavator and a mobile crusher

Factory tour
Unfortunately for me this company visit was more focussed on the products than on the production.

So the only relevant thing I’ve seen was during a small ride with a bus through one of the production facilities. This hall contained two lines for assembling the bulldozers. One was an assembly line with about 8 stations and multiple workers per station. Different sized models are assembled here in a mixed sequence. The other line was more project based, meaning that more than 10 workers assembled the entire bulldozer at once. This was done for the most complex models. Work instructions were giving on a large screen next to the workstation.

The rest of the time we spent visiting the training center and the real life test facilities.

Observations
The production facilities all looked very clean and well organized. While the production halls themselves were very empty, outdoors we found a lot of inventory of all kinds, from raw materials to finished product. This seems a bit weird, while the company’s strategy is to do everything Just-In-Time. But a possible reason for this could be the economic situation at this moment.