# PRODUCT LAYOUT AND ASSEMBLY LINE OPTIMISATION

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**Abstract:** *The product layout, often referred to as a line layout or flow shop, is a widely used approach in both the manufacturing and service industries. It is characterised by the linear or sequential arrangement of workstations, equipment, personnel and processes in order to optimise the flow of materials or services. This chapter explores the concept of product layout in manufacturing and services, its advantages and disadvantages and its application in different industries. Simple line balancing example is presented, including determination of cycle time and required number of workstations, task assignments to workstations and calculation of the line balancing efficiency. Assembly line optimisation focuses on minimising idle time (when the theoretical minimum number of workstations or a satisfactory efficiency level is reached). Some open questions about line optimisation and solutions are briefly discussed too.*

**Key words:** *Product layout, Manufacturing, Services, Line balancing, Optimisation.*

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## 1. Introduction

Production design is a complex task that can be solved with a variety of approaches (Vujica et al., 2021). Knowledge in this field is broad, but this chapter is about understanding how it works in high-volume manufacturing and the service sector.

Layout planning plays a crucial role in both the manufacturing and service industries, as it has a direct impact on efficiency, productivity and cost effectiveness. In manufacturing, an optimised layout ensures a smooth workflow, reduces material handling time and minimises bottlenecks, resulting in higher production and lower operating costs. In the service industry, effective layout planning improves the customer experience and service delivery by organising spaces to make the best use of resources and minimise waiting times. A well-designed layout not only supports efficient operations, but also promotes flexibility, allowing organisations to adapt to changing requirements and technologies. Therefore, layout planning is a fundamental aspect of operational strategy that impacts overall performance, profitability and customer satisfaction.

In general, layout problems deal with the optimisation of spaces and locations (e.g. machines, departments) and are designed to optimise the performance of the system within the facility space. Many research papers have dealt with layout problems and there are several literature reviews classifying the problems, characteristics, solution methods and mathematical models. Various aspects that are closely related to layout problem solving and decision-making are analysed and discussed in (Al-Zubaidi et al., 2021). These aspects are organised as layout drivers: Enabling Technologies, Tools and Techniques, Manufacturing Systems and Supporting Factors. The analysis of these four layout drivers leads to new ideas for the optimisation of the solution and for a robust and sustainable design of the plant layout through the integration of industrial information.

With conventional systems, the layout is rarely changed after the initial design. However, as market demands change more frequently, layout configurations must be able to reconfigure the arrangement of resources to meet new production requirements while minimising material handling and relocation costs and maximising savings in material flow and storage costs (Maganha et al., 2019).

Planning the factory layout is a time-consuming process. Automated planning approaches can generate high-quality layout solutions and reduce planning time compared to purely manual planning. Klar et al. (2023) investigated the performance of different reinforcement learning and some commonly used metaheuristics for three basic layout planning problems of different sizes. The results show that the best performing reinforcement learning approach is able to find similar or better solutions compared to the best performing metaheuristics.

Product layout is a design strategy in which resources are arranged in a linear sequence to achieve efficient and rationalised production or service delivery. In manufacturing, machines and processes are arranged in a sequential order, while in the service sector, the focus is on the arrangement of service stations to minimise bottlenecks and improve the provision of services.

Assembly lines play a crucial role in determining a company's profitability. Market conditions have increased the importance of mixed-model assembly lines (Liu et al., 2021). Fluctuations in demand are common in the real industrial environment and decision makers need to take this uncertainty into account.

Traditional planning methods rely on the planner's expertise and do not use objective criteria to optimise the layout. The manual arrangement of resources is also a time-consuming process, the automation of which has the potential to reduce the manual effort required during the planning process (Michniewicz et al., 2017).

Leiber et al. (2022) present a method for the automatic creation and optimisation of three-dimensional layouts for assembly lines. It is based on a resource library with digital models of the available production resources. These models contain the relevant properties of the resources, including economic characteristics such as their price and technical characteristics such as a description of their working area. A genetic algorithm generates and optimises possible layouts for a line. The optimisation aims to minimise the area of the line and the cost of assembling the line while optimising the positioning of the resources to perform their tasks. The cycle time of the line is considered as a constraint. A multi-body simulation is carried out to evaluate different layout alternatives. The presented system is very flexible and supports the positioning of several resource types.

### *1.1 Product layout in manufacturing*

In a product layout, materials, parts and assemblies move through the production process in a linear sequence, usually following a fixed path (Fig. 1). For organisational reasons, we divide production lines into two basic types: manual assembly lines and automated production lines. However, hybrid lines that include both manual and automated operations are not uncommon (Groover, 2010). In manufacturing, the product layout is typically used to produce standardised products in high volumes or a family of related products, allowing for consistent processes and minimal variation. Each workstation on the production line is specialised for a specific task in the manufacturing process. A good example of this is an assembly line in the automotive industry, where each workstation contributes to the assembly of a car.

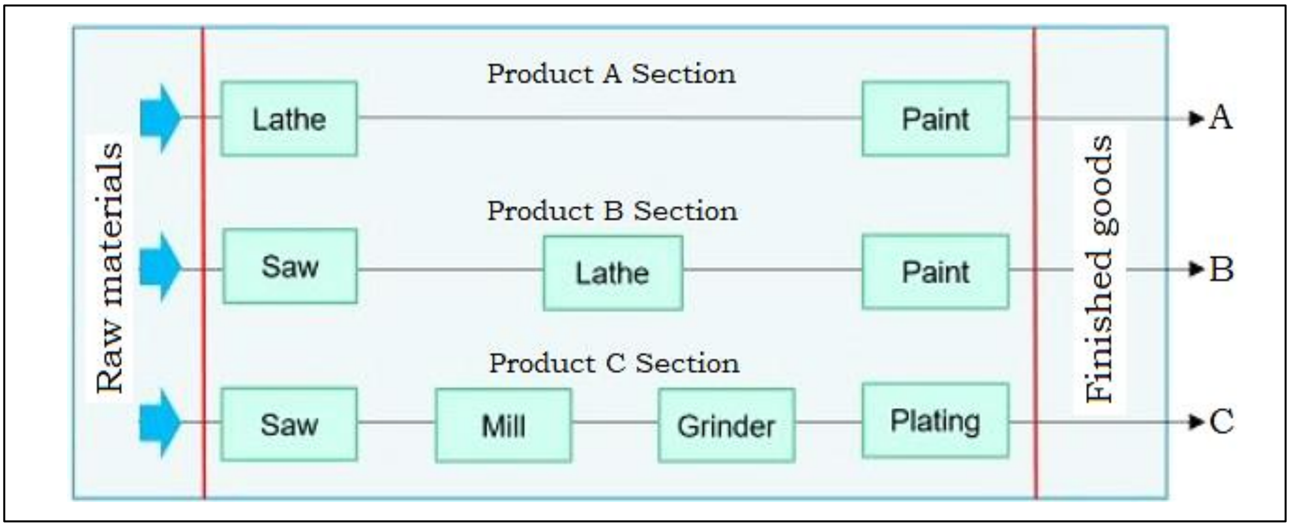


Fig. 1. Product layout for three standardised products.

Individual operations are closely interlinked and must be balanced so that one operation does not block another. Further prerequisites are: a sufficiently large production volume, the product is in an earlier phase of the life cycle, stable product sales, a reliable and high-quality supply of input materials, ... The assembly line balancing problem solves one of the following objectives: assembly with a minimum number of workstations for a given cycle time (takt time) or for a given number of workstations, minimising the cycle time (and maximising the output rate). Product layout offers several advantages:

1) High efficiency: The product layout enables continuous production, minimises idle time, maximises resource utilisation and improves efficiency. The product layout is designed for high productivity, minimising material handling and reducing work-in-progress inventory. The production line operates continuously, often 24/7, to maximise output. Product layouts are known for their high production rates and low unit costs. As the materials move along a fixed path, the need for material handling equipment and labour is reduced.
2) Lower labour costs: Standardised processes reduce the need for skilled labour, which lowers labour costs. Workers specialise in their tasks, which simplifies training and shortens the learning curve (improved productivity). Unit costs are low due to the high volume.
3) Consistency: It ensures product consistency and quality through standardised procedures.

However, there are some drawbacks:

1) Lack of flexibility: Product layouts are less adaptable to changes in product design, product specifications or fluctuations in demand. Changes are difficult and expensive.
2) Initial setup costs: Setting up a product layout can be costly (capital intensive) and time consuming.
3) Monotonous work: Workers may find their tasks repetitive, which can lead to problems with motivation and job satisfaction.
4) Machine downtime – the biggest disadvantage of the product layout: If a single workstation breaks down or an operator is unavailable, this becomes a bottleneck and the entire production comes to a standstill.

Production lines can be designed to cope with variations in product models. Three types of production lines can be distinguished: single model production lines (produce only one model), batch model production lines (produce two or more different product models, but each model in batches) and mixed model production lines (produce multiple models; the models are intermixed).

Line production is divided into two groups: mass production and continuous production. Mass production generally refers to assembly line production (e.g. in the automotive industry). Continuous production is represented by the so-called process industry (e.g. chemical industry, steel industry, breweries, cement industry, energy production).

Although both types are characterised by line flow, continuous processes tend to have a higher degree of automation and produce more standardised products. Line production is maximally efficient, but also extremely inflexible. A large proportion of the processes are automated by machine, the rest are standardised as routine activities. The production volume is large enough to justify the high cost of specialised equipment (Buchmeister, 2024).

### *1.2 Product layout in services*

In the service sector, product layout focuses on organising service stations in a sequential manner to efficiently deliver a particular service or set of related services, minimise waiting times and improve customer satisfaction. Each service station specialises in providing a particular aspect of the service. An example of this is a fast food restaurant where customers move in a linear queue from ordering to picking up their food. The product layout is also frequently used in the banking and healthcare sectors. The benefits of this layout in services include:

1) Reduced wait times: Customers experience shorter waiting times, which leads to greater satisfaction. The product layout enables fast and efficient service for customers.
2) Efficient resource allocation: Service providers can allocate resources based on demand patterns and thus avoid over- or understaffing. Employees specialise in their roles, making training more efficient.
3) Consistency: Standardised service procedures ensure a consistent customer experience.

However, service layouts can be challenging to manage fluctuations in customer demand and may not be suitable for services that require a high degree of customisation:

1) Lack of flexibility: Service layouts can be difficult to adapt to fluctuations in customer demand or specific customer requirements, or to accommodate variations in service specifications.
2) Impersonalisation of customers: The standardised approach can lead to customers feeling like they are being treated like they are on an assembly line rather than receiving a personalised service.
3) Inefficiency in customised services: Services that require a high degree of customisation are not well suited to product layouts.

## 2. Application of product layout in different industries

Product layout is employed in various industries, from manufacturing to services. Let's examine how it is applied in a few key sectors.

### *2.1 Manufacturing*

<u>Automotive industry</u>

The automotive industry is a prime example of the application of product layout. Assembly lines in the automotive industry are designed to produce large quantities of vehicles with high efficiency and quality control. The components and workstations are arranged in a sequence that enables continuous production. A line usually produces one type of a vehicle.

Electronics manufacturing

In the manufacture of electronic products, especially consumer goods such as smartphones and computers, the product layout is very important. This layout optimises the production of standardised electronic components and devices.

*2.2 Services*

Fast-food restaurants

Fast food chains use the product layout to rationalise the order-to-service process. Customers usually follow a linear path from ordering to receiving their food. This layout is designed to maximise speed and efficiency while ensuring consistency of service.

Supermarkets

Supermarkets use the product layout to organise the goods on display in a logical sequence. Items are organised according to customer flow so that customers can move around the shop efficiently and find what they need.

## 3. Assembly line balancing

The assembly line balancing problem is a non-deterministic polynomial-type planning problem for mass production. Changes in layout represent an important decision involving investments for assembly operations, and numerous heuristics for solving the assembly line balancing problem have been described in the literature (Avikal et al., 2013).

In a general sense, the term assembly line refers to a progressive assembly connected by a material handling device (usually a conveyor belt). The formal structure of assembly lines, where people, machines or robots assemble the parts into the product, can be U-shaped, straight or branched (Zhang et al., 2018). When designing an assembly line, we start by breaking down the process into elementary tasks, each of which represents a separate unit of work (Martinich, 1997). The basic line balancing problem assigns the individual work elements (tasks) to the workstations so that they have approximately the same time workloads. There are two good reasons for this: to make efficient use of labour and to avoid problems of fairness that arise when one workstation has to work much harder than another (Hopp & Spearman, 2008). The objective is to minimise unit assembly cost (Askin & Standridge, 1993; Li et al., 2021). The assembly costs are made up of the labour costs for performing the tasks and the costs for idle time. Since the times for the tasks are fixed, we can simply focus on minimising idle time. Each workstation works on a product by either adding parts or completing assembly operations. Workstation features related to the position of workers on the line include the following approaches: workers may sit, stand, walk the line, or ride the line. Worker movement requires some additional time to return to the starting position. In the era of Industry 4.0, robots are used on a large scale to achieve high productivity, better quality and lower costs. When planning a robotic assembly line, production managers are concerned about the costs associated with developing such a system. A popular approach in the manufacturing industry is to develop an assembly line with human-robot collaboration (Şahin & Tural, 2023). Such assembly lines are mainly analysed with deterministic task times. In real life, however, there are stochastic processes in the balance of assembly lines.

Line balancing is usually performed to minimise imbalances between machines or personnel while achieving the required production output of the line (Heizer et al., 2020). It can be done by different methods, such as exact, heuristics, metaheuristics methods, or simulation. In order to produce at a certain rate, management must know the tools, equipment and working methods used (Mura & Dini, 2016). There are two aspects that are very important from an economic point of view: the number of highly skilled workers needed to carry out the operations correctly and the number of assembly equipment along the line. Then the time required for each assembly task (e.g. drilling a hole, tightening a nut or painting a part) must be determined. We assume that the times for the tasks are constant and independent of each other. Some studies deal with the allocation of workers and tasks, whereby task times depend on the qualification levels of the workers (Samouei et al., 2016). Management also needs to know the precedence relationship between the activities, i.e. the sequence in which the different tasks must be performed (Chase et al., 2005). Using this task data, we create a precedence diagram that shows the sequence of required activities (tasks, operations) and the corresponding constraints on implementation (some similarity to the project network chart exists). The diagram approach we use is called an activity-on-node (AON) network, in which the nodes represent the activities and the arcs represent the precedence relationships between them (Krajewski et al., 2018).

Next comes the calculation of the required cycle time, which must be calculated from the customer demand or from the bottleneck time. Two terms need to be clarified. The cycle time is the maximum time available to complete a task or process step. Several process steps may be required to complete a product. Takt time is determined by the customer and is the speed at which finished units must be produced to satisfy customer demand.

The cycle time has two limits: the minimum possible cycle time is limited by the longest task time (lower time limit); the maximum cycle time is equal to the sum of all task times (here we have a workstation and a fixed-position layout).

Then we calculate the theoretical minimum number of workstations (workers) based on the total task time and the cycle time. In the next step, we assign the tasks to the workstations (so that the idle time can be minimised) by considering the cycle time constraints (we eliminate the tasks for which there is not enough time at the workstation) and the sequence dependencies (we eliminate the tasks whose precedence relationship is not satisfied). We use a ranking or prioritisation for the assignment of activities. Mainly some simple line balancing heuristics are used:

- Longest task time – choose the available task with the longest task time,
- Shortest task time – choose the available task with the shortest task time,

- Most following tasks – choose the available task with the largest number of following tasks,
- Least number of following tasks – choose the available task with the least number of following tasks,
- Least number of predecessors – choose the available task with the least number of predecessors,
- Ranked positional weight – choose the available task with the largest sum of the task and all tasks that follow,
- Random – choose the task randomly from the set of available tasks, etc.

Although heuristics provide solutions, they do not guarantee an optimal solution. After we have assigned all tasks, we calculate the line balancing efficiency. Typical line balancing efficiencies in industry range between 0.90 and 0.95 (Groover, 2010). We terminate the programme when the theoretical minimum number of workstations or a satisfactory efficiency level is reached, or we repeat the task assignment with a different decision rule (line balancing heuristic). The balance can often be improved by reassigning workers according to skill and speed, by assigning additional workers to bottlenecks, by changing the speed and capabilities of support equipment according to the workload assigned to the workstations, and by checking the compatibility of the tasks at the workstations and changing the task assignments accordingly.

### *3.1 Line balancing example*

The toy car S is to be assembled on a conveyor belt. 500 units are required per day. The assembly principle is shown in Fig. 2.

Fig. 2. The toy car S assembly principle.

Production time per day is 420 minutes. The assembly tasks, task times and the precedence data for the toy car are given in the Tab. 1 below.

| Task | Task description | Task time [s] | Immediate predecessors |
|---|---|---|---|
| A | Position rear axle support and hand fasten four screws to nuts | 45 | - |
| B | Insert rear axle | 11 | A |
| C | Tighten rear axle support screws to nuts | 9 | B |
| D | Position front axle assembly and hand fasten four screws to nuts | 50 | - |
| E | Tighten front axle assembly screws | 15 | D |
| F | Position left rear wheel and fasten hub cap | 12 | C |
| G | Position right rear wheel and fasten hub cap | 12 | C |
| H | Position left front wheel and fasten hub cap | 12 | E |
| I | Position right front wheel and fasten hub cap | 12 | E |
| J | Position handle shaft on front axle assembly and hand fasten bolt and nut | 8 | F, G, H, I |
| K | Tighten bolt and nut | 9 | J |

Tab. 1. The toy car S assembly tasks, task times and sequence requirements.

Request: find the balance that minimizes the number of workstations, subject to cycle time and precedence constraints. Tasks with the longest task time are assigned first (primary rule). In case of a tie, choose a task, which is higher in the list (secondary rule).

Solution:

1) We draw a precedence diagram illustrating the sequential relationships (Fig. 3).

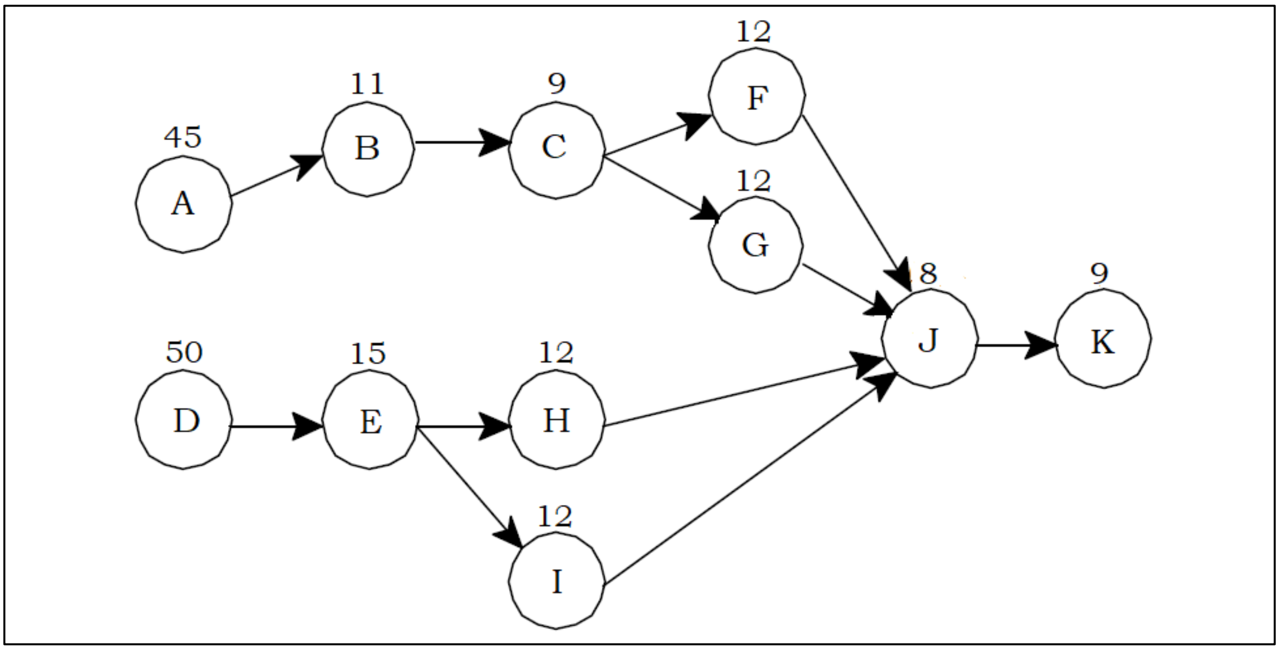


Fig. 3. Precedence diagram for the toy car S assembly.

$$\text{Total Cycle Time} = T = t_A + t_B + \ldots + t_K = 45 + 11 + \ldots + 8 + 9 = 195 \text{ s} \quad (1)$$

2) We determine workstation cycle time $C$:

$$C = \frac{\text{Production time per day}}{\text{Output per day}} = \frac{420 \cdot 60 \text{ s}}{500 \text{ units}} = 50{,}4 \text{ s} \quad (2)$$

3) We determine the theoretical minimum number of workstations ($N_t$) required:

$$N_t = \frac{T}{C} = \frac{195 \text{ s}}{50{,}4 \text{ s}} = 3{,}87 = 4 \quad (3)$$

4) We make task assignments to form workstations (Tab. 2). This grouping must satisfy the precedence relationship and total time at each station cannot exceed 50,4 seconds.

| Workstation | Remaining time [s] | Feasible tasks | Time appropriate tasks | Assigned task | Task time [s] | Unused time [s] |
|---|---|---|---|---|---|---|
| 1 | 50,4 | A, D | A, D | D | 50 | 0,4 |
| 2 | 50,4 | A, E | A, E | A | 45 | 5,4 |
| | 5,4 | B, E | - | - | - | 5,4 |
| 3 | 50,4 | B, E | B, E | E | 15 | 35,4 |
| | 35,4 | B, H, I | B, H, I | H | 12 | 23,4 |
| | 23,4 | B, I | B, I | I | 12 | 11,4 |
| | 11,4 | B | B | B | 11 | 0,4 |
| 4 | 50,4 | C | C | C | 9 | 41,4 |
| | 41,4 | F, G | F, G | F | 12 | 29,4 |
| | 29,4 | G | G | G | 12 | 17,4 |
| | 17,4 | J | J | J | 8 | 9,4 |
| | 9,4 | K | K | K | 9 | 0,4 |

Tab. 2. Task assignments to workstations 1 to 4.

5) We calculate the line balancing efficiency using actual number of workstations:

$$\text{Efficiency} = \frac{T}{N_a \cdot C} = \frac{195}{4 \cdot 50{,}4} = 96{,}7 \ \% \quad (4)$$

6) The evaluation of the solution shows that the result is not bad, but there is another possibility for improvement: we can reduce the cycle time for the minimum unused time taking into account all workstations: 0,4 s. The new cycle time will therefore be 50 s. (Another way to optimise the line is to rebalance with a different decision rule.)

$$\text{Efficiency}' = \frac{T}{N_a \cdot C} = \frac{195}{4 \cdot 50} = 97{,}5\ \% \tag{5}$$

7) Actual output per day (production rate):

$$\text{Output per day} = \frac{\text{Production time per day}}{C} = \frac{420 \cdot 60\ \text{s}}{50\ \text{s}} = 504\ \text{units} \tag{6}$$

8) Actual assignment of tasks to 4 workstations is shown below (Fig. 4).

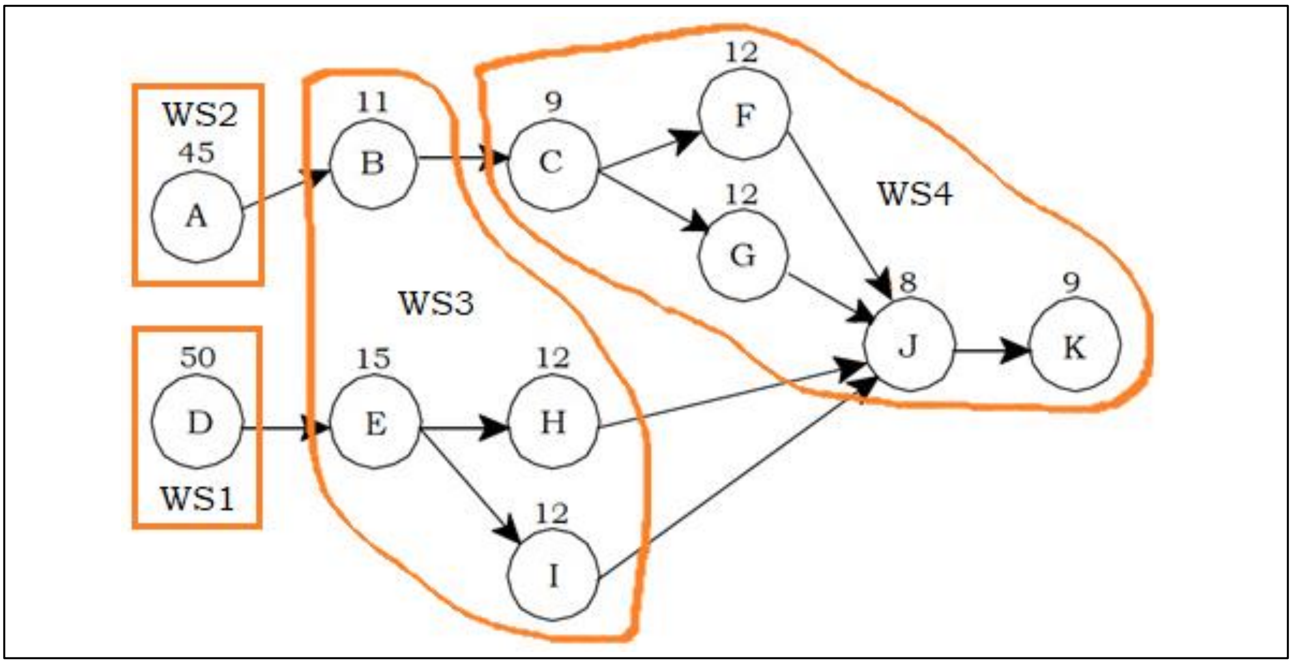


Fig. 4. Assignment of tasks to 4 workstations for the toy car S assembly.

*3.2 Discussion about line optimisation and solutions*

Manually shifting tasks can be quick, but does not always lead to the most efficient overall balance. There are many software tools for assembly line balancing. They can quickly balance and visualise thousands of tasks, hundreds of models and options, hundreds of customer orders and satisfy the largest number of hard and soft constraints such as precedence, resources, work zones, grouping, ergonomics, inspection and product orientation. An example of the Proplanner application is shown in Fig. 5. Some additional features:

- When tasks are moved in a balance, all associated data is moved with them, including required parts and tools, models and options, standard time, value add analysis, images, and other task details.
- Each chart view and report within the line balancing provides an aggregated and detailed analysis of the varying labour times required by each product model and/or option.
- Users can provide an order file, and with this information, the weighted average labour time across all units can be considered in addition to the most common and worst-case configurations.

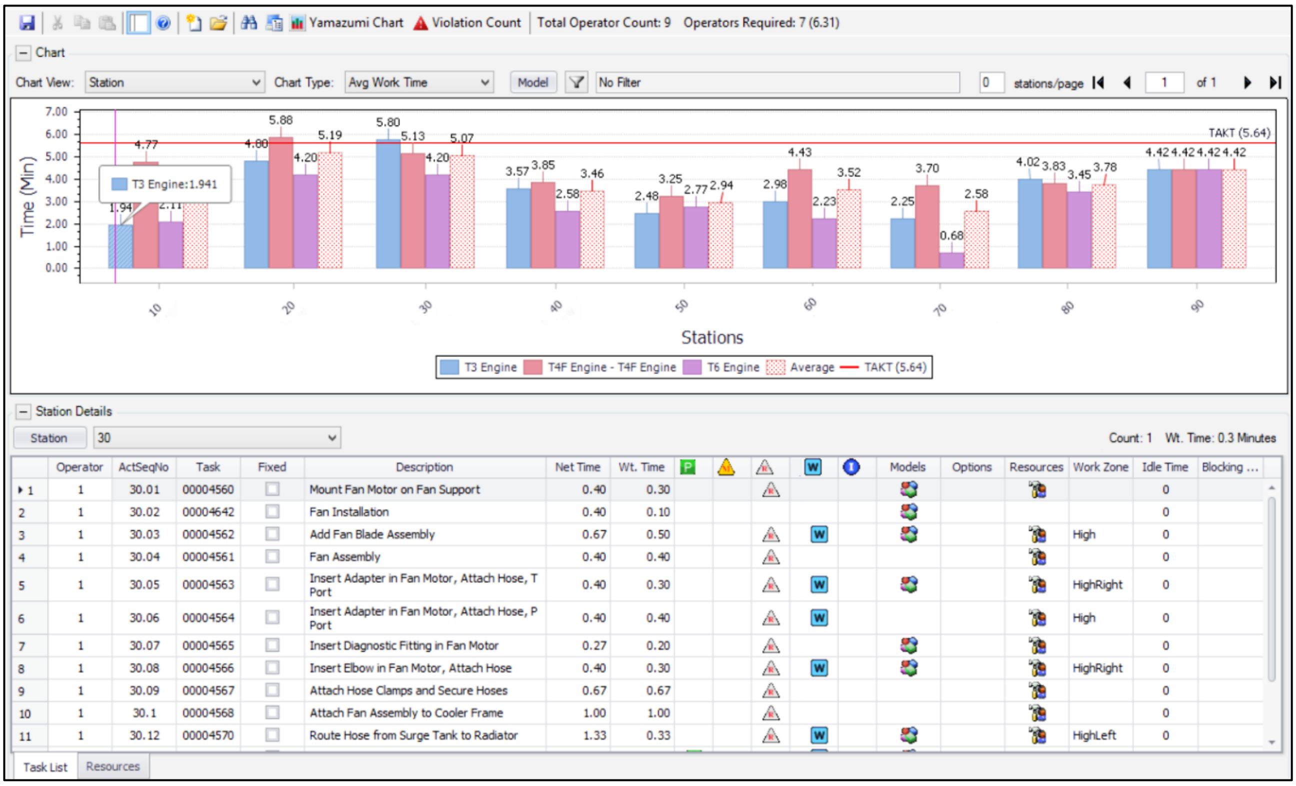

Fig. 5. Assembly line balancing in Proplanner.

Randomness in processing (task) times leads to a decrease in the effective output rate. Some of the main causes of variations in processing times are variations in the quality of materials, human variations due to fatigue, lack of materials, defects, mechanical failures, changeovers to produce different products and differences in batch size. The amount of variation can often be reduced through better training and workplace design, better quality management procedures, better sequencing and scheduling, and better maintenance procedures (Martinich, 1997a). Another possible measure is the use of an alternative to a conveyor-paced assembly line: a sequence of workstations linked by gravity conveyors that act as a buffer between successive operations (Kumar & Suresh, 2008).

Often the longest task time is greater than the workstation cycle time of the production line. What can we do? Several possibilities are available:

- Split the task.
- Share the task (an adjacent workstation does part of the work).
- Use parallel workstations.
- Use a better skilled worker.
- Work overtime.
- Redesign the product.
- Upgrade equipment. Etc.

Often, exploring a range of cycle times makes sense too.

The arrangement of workstations in a process can be described on a spectrum from “long thin” to “short fat” (Fig. 6). Long or short describes the number of workstations; fat or thin describes the amount of work at each workstation.

In a given situation, there are usually technical constraints that limit either how "long and thin" or how "short and fat" the process can be, but there is usually a range of possible options within which a choice must be made (Slack et al., 2022).

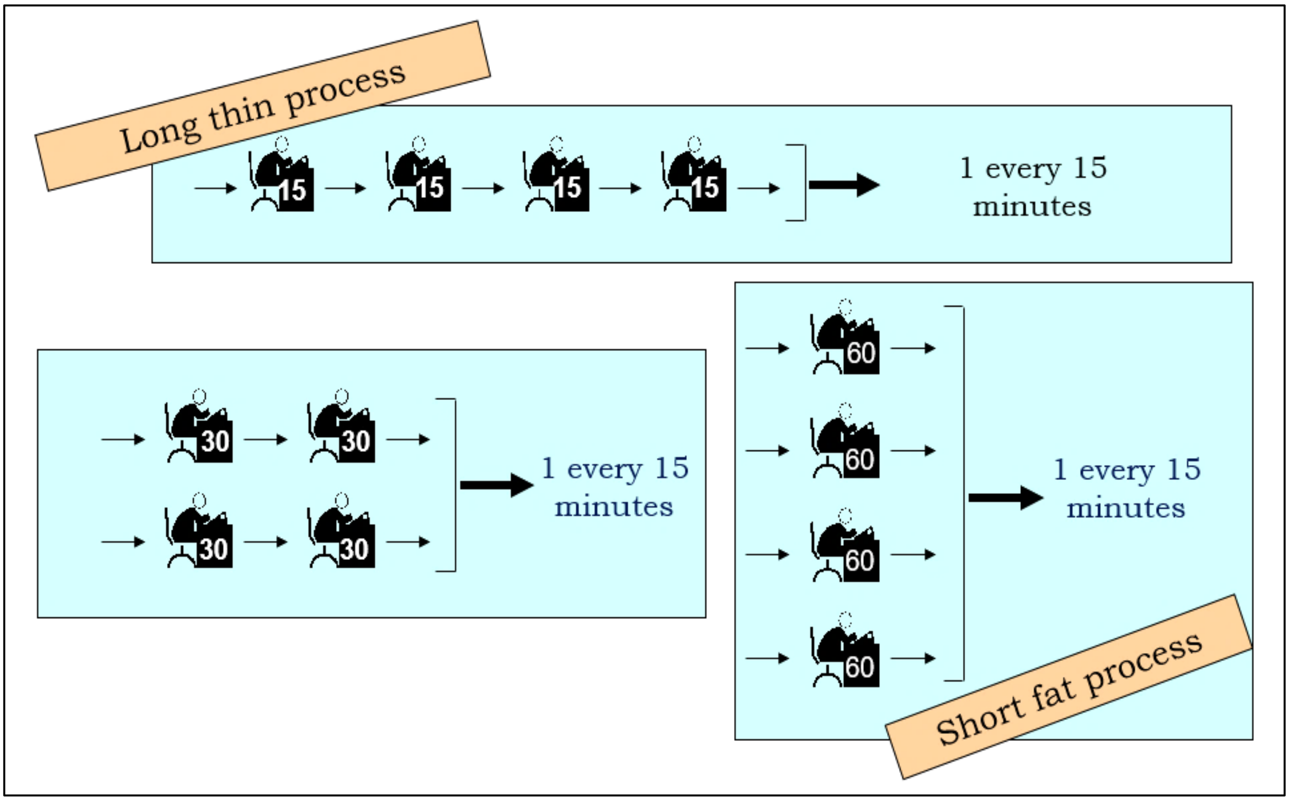


Fig. 6. Long and thin versus short and fat layouts in a case of a 60-minute task with a required cycle time of 15 minutes (Slack et al., 2022).

Advantages of long-thin processes:

- controlled flow of items,
- simple materials handling,
- lower capital requirements (no duplication),
- greater efficiency,
- higher space utilisation.

Advantages of short-fat processes:

- higher mix flexibility,
- higher volume flexibility,
- greater robustness,
- less monotonous work.

The most controversial aspect of product layout is the behavioural response. Studies have shown that a high pace of production and a high degree of specialisation reduce job satisfaction (problem of monotony). Many companies are exploring job enlargement and rotation to increase job variety and reduce over-specialisation. This approach increases employee responsibility, boosts morale and increases output (up to 10 %).

Fig. 7 shows an idea that Toyota has implemented at its Miyagi factory in Japan to make the assembly lines even more efficient. The illustration shows how Toyota has positioned the vehicles sideways rather than lengthways as usual. This makes the line 35 % shorter (increasing space utilisation) and shortens the distance workers have to travel between vehicles (increasing workflow efficiency).

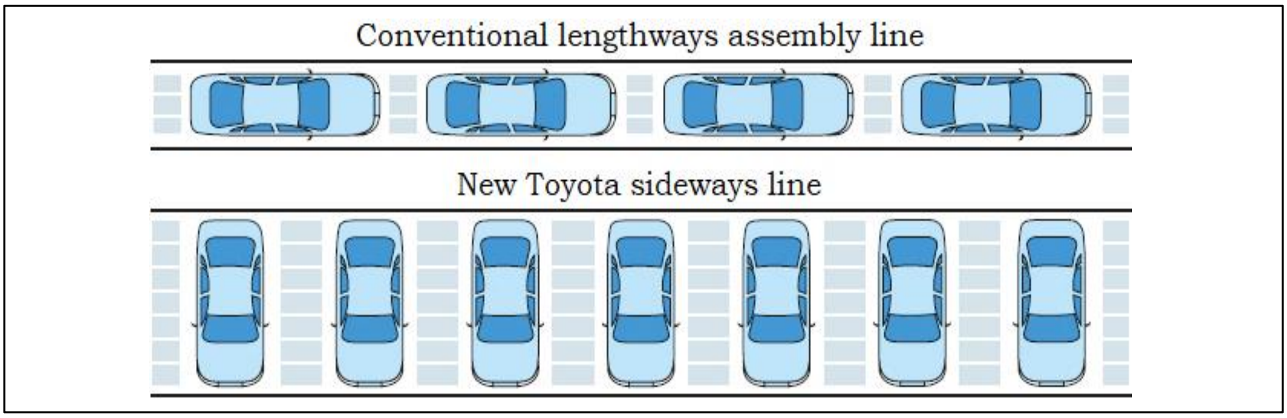


Fig. 7. Contrasting arrangement in product layout for a vehicle assembly plant (Slack et al., 2022).

## 4. Conclusion

Industries that manufacture their products on assembly lines are currently facing major challenges. The first is the need to assemble a large number of product models and their variants on the assembly line due to the variety demanded by the market. Another challenge is the need to maintain an appropriate level of labour and other resources employed.

The way the product (line) layout is decided is slightly different from the other layout types. This is not about where to place what, but rather what to place where. Precedence lays down what operations must precede others, what can be done at the same time and what must wait. The precedence requirements are an important input for the product layout. Often locations are determined and then work tasks are assigned to each location (Slack et al., 2022).

In line layout, the detailed design of product layouts involves a number of decisions, such as the cycle time to which the design must conform, the number of workstations in the operation, the way in which tasks are assigned to the workstations in the line and the arrangement of the workstations in the line. As this is a continuous process, a finished product comes off the production line at the end of each cycle (Khanna, 2015).

Product layout, whether in manufacturing or in the service sector, offers a systematic approach to optimising the use of resources and rationalising processes. While it has its benefits in terms of efficiency and cost reduction, it may not be suitable for all types of products or services, especially those that require a high degree of customisation. Successful implementation requires careful consideration of industry-specific requirements and customer preferences (Yang et al., 2019). Line flow production is maximally efficient, but also extremely inflexible.

As industries continue to evolve, product layout remains a valuable strategy for companies looking to improve operational efficiency and customer satisfaction.This chapter provides an overview of product layout planning methods for a flow shop (supported by an example), some recent developments in the literature and a discussion of line optimisation and applicable solutions.

As a recommendation for our future work, the comparison between balancing heuristics and metaheuristics can be mentioned, taking into account the results obtained and the computing time required.

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