



Learning Objectives for This Chapter

- role of factory planning in SCOM
- factory planning processes
- role and methods of capacity planning
- options for process flow design
- lean production systems
- modern trends: Industry 4.0

9.1 Introductory Case-Study “Factory Planning at Tesla”

The location of a new factory can provide competitive advantage and has strategic relevance for every company. For once, location influences cost structures. For example, producing in a low-wage country influences the production price of the product. Risks are constituted by politics, exchange rates and currency swings. Many companies operate in various countries making use of the advantages in each location.

On the other hand, innovation plays another important role for business success. Proximity to universities, research areas or other enterprises operating in the business can enhance innovation incentives. Here, qualified employees are also easier to reach, for example through recruiting from universities. Much of the time governments will support particular areas with tax advantages to trigger the development of innovation clusters. In these areas the infrastructure is well developed.

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Therefore, supplies are easily delivered to the area and finished products to the retailer or end customer. The location of the market, where the customer is located, is also relevant.

E-mobility is the new trend in the car industry. With decreasing amounts of fossil fuel electricity is an attractive option to pursue while helping to protect the environment. But there is criticism that some factories are not zero emission producers but simply reallocate the emissions elsewhere. Batteries need to be charged by power plants and batteries are difficult to produce. Nevertheless, researchers found that electric cars still save energy and are more environmentally friendly than gasoline or diesel operated vehicles. According to experts, e-mobility could reduce CO₂ emissions by 47% by 2030. Companies have discovered this trend and have been trying to find the most efficient versions of e-mobility. The biggest obstacle is still presented by batteries. Many are expensive to produce or do not last very long. Moreover, safety issues have to be resolved. Development of lithium-ion batteries has brought major advancement. Many governments support the implementation of non-fuel systems. The so-called original equipment manufacturers (OEM) are constantly developing new electric vehicles.

Tesla is one of the new generation enterprises on the e-mobility scene. Recently, Tesla Roadster and Tesla S presented models for the mass audience. A third one is planned—a sports version. The cars have a relatively low noise level, zero emission and cost approximately \$35,000. This constitutes serious competition for long established OEMs.

Tesla's production plant is located in Fremont, California. The city is located right in the heart of the prestigious Silicon Valley research area. Here many companies have settled, producing basically everything technology has to offer. Silicon Valley became popular in the 1980s and 1990s, and is called a post-fordistic complex with special dynamics. There are various advantages to this location. Its proximity to technology-savvy Stanford University is just one of them. So-called knowledge dynamics and well-educated, highly qualified employees along with a fiscal friendly policy attract enterprises. Additionally, military and aircraft industries are close by, which support location factors which are already beneficial. A supplier network has been developed and established. Moreover, Silicon Valley is located near San Francisco, which offers a good working atmosphere for its employees.

There are also downsides to the technology cluster. The infrastructure is highly overloaded. While people have continuously moved to the area, the infrastructure has not kept pace with demand. Additionally, rent prices have exploded, making it especially difficult for smaller companies to rent office space. Very often, small start-ups turned out to be the most successful enterprises.

Tesla purchased a dormant production plant in Silicon Valley from Toyota, which uses relatively little of the huge factory space. Various suppliers deliver lightweight components to the plant by trucks. The long waiting time for Tesla S' customers, currently around 4 months, is especially problematic. This is mainly due to the shortage of lithium-ion batteries supplied by Panasonic.

In the plant there are eight robots in each assembly line. Usually, a robot is able to fulfil only one task; however, Tesla's robots are able to handle four at once. Tesla S is the model currently on the production line. Processing time at each station

(so-called *takt time*) is 5 min and the *total production lead time* (PLT) (so called *cycle time*) takes 3–5 days. This is still quite long compared to large car manufacturers. Eighty Tesla S cars are built on the site every day. In the first year 20,000 cars were planned, which is rather a small number compared to Tesla’s big competitors such as Hyundai and Beijing Motors. Tesla started its business around 10 years ago and is still working on a much smaller scale. Nevertheless, it is fairly successful. Currently, Tesla is upgrading the factory for the assembly of an SUC model or a sports car. The assembly line will remain the same; only the robots have to be reprogrammed. This factory concept is extremely flexible and saves enormous investment costs compared to building a new production line or plant.

Questions

What are advantages of the factory location in Silicon Valley?

What are the general advantages of Tesla’s production layout?

How could the lead-time problems be resolved?

What problems could Tesla potentially face in the future?

How many cars could be produced in 8 h by Tesla if the takt time could be reduced to 3 min?

9.2 Factory Planning

9.2.1 Role of Factory Planning in SCOM

Factory planning and *process design* problems occur when, for example, an existing factory requires adaptation in order to make sure that new products can be produced using the existing infrastructure. Planning and design could also be required to implement new technology into the production process so that through-put times can be reduced. These are just two typical problems when the factory has to be modified to generate competitive advantage.

But there are also problems related to the creation of completely new factories. The erection of a completely new manufacturing facility is also considered the “green-field approach”, compared to the “brown-field approach” when modifying existing plants.

Sometimes it might also be necessary to centralize the so-called *production footprint*, which means that factories might be adjusted in their size (expanded or reduced) in a case where factories might be closed or parts of old ones might be reactivated. Current challenges in the business demand dynamic, adaptable, scalable and modular factories (Wiendahl et al. 2005; Schenk et al. 2014). This is related—among many other influencing factors—to shorter product life cycles and shorter time-to-market requirements as well as improvement in production technology. Additionally, a fast reaction to changing market needs and technological conditions requires the design of new and modular factories. Grundig (2015) provides a very structured and systematic approach on the processes and steps in factory planning.

A new, *modular factory* is the one that BMW created in Leipzig, Germany. This facility covered the three main production areas of the car—body shop, paint shop and final assembly. The important aspect is the scalability and the expansion potential the factory has in order to enable adjustments to its layout in accordance with market development. Recently the Leipzig plant has been expanded in order to produce BMW’s electrical vehicles as well.

It becomes evident that the spectrum of “factory planning and process design” covers a broad variety of practical problems that are approached in a structured way. It is the purpose of this chapter to elaborate on the approach and steps taken to solve the challenges summarized above.

9.2.2 Processes of Factory Planning

Systematic factory planning is related to a planning cascade, also referred to as a “*planning pyramid*”, from the initial idea, through the process of the ideal factory, to the detailed elaboration, to when the factory finally operates. In general, one will need to consider the steps of target planning, concept development, elaboration and evaluation of alternatives and execution of the selected alternative leading to the final factory building.

Three basic *processes in factory planning* can be classified as in Table 9.1.

Table 9.1 Factory planning processes

Phase	Main contents or results to be achieved
Planning	<ul style="list-style-type: none"> Collection of requirements (e.g. production programme); Analysis of tasks that need to be performed; Health, Safety and Environment (HSE)/feasibility studies that need to be considered; Description of functional areas and expected output, layout alternatives; Layout models/site layout plans to be presented; Required documents to obtain authority approval.
Realization	<ul style="list-style-type: none"> Statements of work (e.g. also for subcontracting purposes); Screening of quotations/offers to be evaluated; Detailed project plans and related information on realization and capacity planning (who/which company is going to work when on what to be finalized by when (this is a very challenging task for the project management team); Purchasing plans for heavy equipment (e.g. robots, transportation devices, machines, logistical equipment, cranes. . .); Plans for the IT installations such as terminals for shop-floor management, etc.; Plans for departmental commuting; Plans for the training or hiring workforce.
Operation	<ul style="list-style-type: none"> Plans on the final approval and commissioning of the factory and its functional areas to make sure it can be operated; Documents to be obtained from external approval bodies, quality certificates, HSE and construction approval; Planning of the ramp-up phase including training and education of the workforce, Preparation for start of volume production.

Consider these processes in more detail.

Planning pre-requisites and factory planning preparation consists of the collection of the relevant short-, medium- and long-term inputs for the factory planning project. This *target planning* is the input for structuring the process and for creating the planning documentation. The results from this first block create the precise formulation of the tasks and targets/objectives of the factory planning process and have contributed to a first or pre-feasibility study.

9.2.2.1 Factory Structure Planning

This complex deals with the creation of the first high-level factory layout designs which support the evaluation of alternative concepts for the factory. It is important to mention that in this case an ideal view is taken, which means that potential constraints regarding the available infrastructure or pieces of land are not considered. The reason for this disconnected view is to develop the most appropriate structure (*principle planning*), the identification of the main production areas, the necessary assembly processes and also the required logistical flows and set up.

In other words, this planning complex has the objective to evaluate and select the most appropriate structure under the best conditions and it also aims at dimensioning the functional areas. Furthermore the connection and logistical linkages as well as the process sequencing are advanced by the factory planning team so that an *ideal layout* of the factory can be presented. Once this has been agreed to, adaptation to the real existing or available conditions is made. This transfer from the ideal scenario to what can be achieved is leading to the generation of the so-called *realistic layout*. The different variants presented (scenarios) can be mentioned as well as the related *feasibility study*.

Still, it might be necessary to de-couple functional areas due to vibrations (e.g., a press shop), and to separate buildings in order to comply with local construction rules and regulations (e.g., fire protection, noise emission, pollution) or to consider a special foundation. These aspects differ from case to case and from country to country so that this will need to be investigated in detail once a decision for a new factory is made in practice.

9.2.2.2 Detail Planning and Project Preparation for Realization

After management has decided on the preferred factory layout variant, the detailed planning (fine planning) takes place. Starting with the block layouts (rough layouts) that were described earlier, the exact allocation and space for machines, positioning of supporting equipment, planning of additional space and office infrastructure (locker rooms, medical support, offices, sanitary space), but also planning of media (gas, water, electricity, information technology...) have to take place. One could say that the "empty facility" of the rough planning is now filled in with its exact functional content (fine planning) so that the factory can finally be created. The deliverable of this process is the factory planning project including all detailed plans.

9.2.2.3 Project Realization

When details are defined, the suppliers and partners will need to be involved in line with the project plan specified. In parallel to all these planning complexes a team will need to make the necessary cost calculations (business case development and validation) followed by running stringent cost controlling. Additionally, the planning needs to be properly set up by a project management team to track progress, to visualize it and to alert in case of deviations. These could be cost, time or quality related deviations. These are typical tasks that will be run under the guidance of the factory planning project management team.

In order to make the factory planning process with typical use case scenarios more transparent for the reader, the short cases are presented as follows:

- An existing factory is regularly adjusted to current production needs.
- An existing factory is completely redesigned to meet strategic objectives.
- A new factory is completely built from scratch in order to generate competitive advantage in a new market.
- Temporary factory with a partner.

9.2.2.4 An Existing Factory Is Regularly Adjusted to Current Production Needs

The factories are planned from a layout and process point of view in a way to ensure flawless execution of all necessary production and assembly steps. This is also done in consideration with the corresponding production system and its underlying Lean principles. The company needs to adjust its production and thus the layout of the factory whenever there is a new product launched. That means the team dealing with factory planning reviews the existing factory, the material flow from the incoming area over the storage area, considers the involvement and allocation of suppliers into the production process, and deals with questions as to how to test the product and how to ship it to the customer. As we can see, factory planning is linked to layout planning, production sequencing and also recognizing the importance of a streamlined material flow. If there are new production or assembly steps, if there are more suppliers that need to be involved, if the existing buildings need to be adjusted or if there is a need to create a new building, this is all done by the factory planning department. As this first case shows, even without creating a completely new factory, the aspect of factory planning plays a crucial role during the normal production of the product portfolio and thus represents a regular task to ensure continuous improvement.

9.2.2.5 An Existing Factory Is Completely Redesigned in Order to Meet Strategic Objectives

In contrast to the above summarized continuous adjustment of the factory to meet current production needs, a complete factory makeover is a task where the location of the factory on the plot of land remains the same, but where fundamental changes

are implemented. Such a complete factory makeover is furthermore based on a strategic decision as it involves significant investment.

Based on inputs from the sales team regarding the expected production programme for the next few years, the resulting capacity needs are derived. That means an understanding is required of what type of product and in what quantity is expected to be placed on the market. This information is provided to the factory planning team on an aggregated level. The factory planners then review the existing setup of the facility and determine which production steps are necessary, what kind of technology is required and what it means in terms of manufacturing hours, stations and number of buildings.

For example, a strategic decision was made to almost double the production volume to satisfy global markets. This would require a complete redesign of the layout, allowing, for example, mixed-model lines with shortened set-up times; it was also strongly linked to the set-up of a completely new logistics concept to feed the assembly lines continuously with material from the warehouse. The warehouse would be completely newly built and so-called logistics trains to be installed to provide the parts and components to the assembly stations. That means that the shape of the building remains the same, but the internal allocations of the stations, the material flow and the allocation of the warehouse have to be completely made over to satisfy the demands of growing markets.

9.2.2.6 A New Factory Is Completely Built from Scratch in Order to Generate Competitive Advantage in a New Market

Factory planning also plays a significant strategic role with respect to the generation of competitive advantage. For example, the Indian market might require new products (e.g., investment goods). To win the corresponding commercial bid, it would be necessary to ensure that the products are made to a very high degree locally in India itself. This is also referred to as “local content”. That means a location needs to be identified to set up a completely new factory, in which local staff would create the final product with a high proportion of locally sourced materials. For this case of factory planning, the aspect of location planning would also be important because the company needs to identify a region in which to create the new factory on green-field site. Under consideration of site selection criteria (e.g., existing infrastructure, availability of potential workforce, appropriate suppliers or capable logistics service providers) a location for the factory has to be identified. The plot of land also has to provide for possible later expansion of the factory. Finally, a completely new facility with internal suppliers on site would need to be created in India.

9.2.2.7 Temporary Factory with a Partner

This is a special case of factory planning, where local content requirements have to be met, but where no new factory has to be created. Imagine that investment goods have to be made for a customer in Romania. Assume that this would be related to a

one-time contract (products are produced, but then no further products have to be made for that customer), there was no business case for a new factory. In such a situation, there would be no business case justifying the creation of a new factory. In order to produce in Romania with local staff for the local customer, the existing infrastructure would be analysed to find already existing facilities that need to meet the necessary requirements (such as infrastructure, size and height of buildings, handling equipment, floor density, etc. . .). In a traditional industrial zone, appropriate facilities could be identified. The available alternatives will be reviewed regarding their strategic and operational fit. Finally, the investment goods might be produced in a factory that originally generated, for example, heavy power plant transformers. Of course, that factory will need to be replanned with consideration for the assembly and logistical processes required to ensure on-time and on-quality delivery of products to the final customer. This example shows that factory planning has to be considered as a strategic decision to be responsive and flexible when it comes to customer focus.

9.2.2.8 Health, Safety and Environment

It is important to emphasize, that in all examples and activities around factory planning, the aspect of HSE has highest priority. HSE deals with the proper working conditions that have to be ensured by the company so that employees can contribute to value adding under safe and healthy conditions. Thus, the workforce has to be provided with personal protection accessories, such as safety shoes, gloves, hard hats, ear plugs, etc. Furthermore, the ergonomic aspects need to be considered and corresponding tools (e.g. lifting or transportation devices) have to be made available. People need to be safe when they perform their work. Safety trainings and education is a mandatory objective. Also, safety and work instructions need to be available for all employees, including instructions on how to proceed in case of an injury.

Factory planning and HSE are strongly connected, as HSE is also related to ensuring proper daylight or illumination, as well as to keeping working areas free from dust (e.g., from welding); smells (e.g., from glues) or from the noise of machines or processing. Also emissions have to be avoided when for example fork lift trucks are charging the batteries: proper emission or smoke evacuation technology has to be installed. A safe workplace means also that emergency exits need to be clearly marked, fire extinguishers are available within easy reach and corresponding visual aids show the shortest path to extinguishers or to the emergency exit. Therefore HSE related topics always have to be on top of the agendas in running operations but also when new operations are planned.

9.3 Capacity Planning

Under *capacity*, we understand the throughput, or the quantity of units a facility can hold, receive, store, or produce in a period of time (Heizer and Render 2014). That means there is a constraint or a limit on production to satisfy demand. This limit can be theoretical and effective.

The theoretical limit is called *design capacity* which is the maximum theoretical output of a system. *Effective capacity* is the capacity a firm expects to achieve given current operating constraints (Heizer and Render 2014). In practice, effective capacity is usually lower than design capacity.

Let us look at capacity using a very simple example. Assume that we have a small bakery shop in a big railway station. If it takes a single person 2 min to prepare a sandwich, then that person can produce 30 sandwiches (60 min per hour/2 min preparation time per sandwich = 30 sandwiches) per hour. So, looking at the aforementioned definition, the total amount that can be produced per hour is 30 sandwiches, in other words the capacity is equal to 30 sandwiches per hour. In this theoretical example, we might have analysed that there are peak demands in the morning hours (8.00 o'clock), during lunchtime (12.00 o'clock) and in the evening (at 17.00 o'clock), when people are travelling back to their homes. During these three peak times, the demand might be 90 sandwiches per hour. That shows two typical operational problems: first we have a capacity issue at the peak times; and second we need to *balance capacity according to demand*. What we could do, for example, is to increase the workforce during times of high demand; or we might use technology to shorten the time to create one product; or we might pre-produce the components of our sandwiches (this could be pre-slicing of the bread or slicing the cheese). This simple example indicates that a company needs to know its existing capacity, so what it is able to perform per period. The company also needs to adjust its capacity respectively and needs to clearly know where the *constraints or bottlenecks* are.

Now, let us translate this way of thinking into the operational world. In order to determine the capacity, it is necessary to know the products that have to be placed on the market. This understanding of demand could be order-driven, and/or it could be forecast driven. In our bakery example, it could be that there is a bank building nearby which placed a fixed order of 50 sandwiches every day. That means that there is an existing contract that specifies exactly the quantity and the composition of the goods. On top of that we know the regular daily demand patterns including the three peaks per day explained at the beginning of this section. The forecasting aspect plays a role when we consider vacation periods or other seasonal aspects. It can also happen that we recognize that daily demand increases about a certain percentage when there is a football game nearby.

All this is very important information for us to understand the demand of products per time unit and how to balance that against our existing capacity. This also tells us that we need to be able to adjust our capacity to cope with swings on the demand side. As a consequence, we need to have the space, the workforce and the machinery and tools to meet the demand. Of course this information on future demand is not only required to determine capacities, but it is also relevant to managing the SC, as the corresponding need for materials needs to be communicated to suppliers. In the simplified bakery example for better illustration purposes, this might be bread, butter, cheese, etc. In real large factory operations, raw materials, purchased parts and components need to be in line with foreseen demand as well as with the required technical and human capacities.

9.3.1 Queuing Theory

Queuing theory is an important tool for capacity planning in services and industries. We find queues for example in supermarkets or in waiting rooms; or there are queues of trucks in front of distribution centres or of several orders that have to be processed in production.

Queuing theory helps to analyse *performance of a process* such as that of the temporal arrival of goods in a distribution centre. Performance generally can be measured in different dimensions such as capacity, time, cost, quality or flexibility and these factors can influence each other. The queuing model is a good tool for analysis of time dimension in a process. In Fig. 9.1, a simple queuing model (one-channel model) is presented.

A queuing model comprises the following elements:

- *input* (e.g., patients)
- *queue* (e.g., patients in the waiting room)
- *processing station* (e.g., a doctor)
- *output* (patients after the treatment).

In queuing theory, different options exist to describe these four elements. To describe the queues we use the notation

$$a/b/c,$$

where

a is probability distribution of arrival rate, e.g.:

- D = degenerate distribution (deterministic)
- M = Markovian distribution (Poisson process)
- G = general distribution;

b is probability distribution of service time

- D = degenerate distribution
- M = exponential distribution
- G = general distribution;

c is number of servers (processing stations)

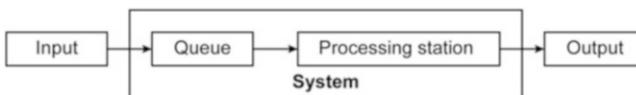


Fig. 9.1 Queuing model

In regard to the number of servers, there are two basic kinds of models. A *one-channel model* considers only one queue and one server that process the input. A *multiple-channel model* is involved with one queue and several servers or several queues and several servers.

Consider a system where there is no constraint in the queue and we follow the rule “first come first serve” for defining the processing sequence. To analyse this case, we introduce some notations that describe the system components (Fig. 9.2).

We consider the so-called M/M/1 queue. We determine mean number of arrivals per time period as λ and mean number of people or items served per time period (i.e., average service rate) as μ . It means that the arrival rate is Markovian distributed, service time exponentially distributed and there is one server. We can find this queue, for example, in post offices or small supermarkets with only one cashier or in waiting rooms for only one doctor’s surgery.

Consider the following formulas to understand how to analyse the performance of the queuing process. To determine the time between the arrivals of two customers, e.g. patients, we use Eq. (9.1):

$$\text{Estimated inter - arrival time} = \frac{1}{\lambda} \tag{9.1}$$

To analyse the service time we use Eq. (9.2):

$$\text{Estimated service time} = \frac{1}{\mu} \tag{9.2}$$

To analyse the *utilization* factor for the system we use Eq. (9.3):

$$\rho = \frac{\lambda}{\mu}; \rho \leq 1 \tag{9.3}$$

To calculate the *probability* of more than n -units in the system, we can use Eq. (9.4):

$$P_n = \rho^n \cdot (1 - \rho) \tag{9.4}$$

To find out the *length of the queue* (e.g., the estimated number of patients in the waiting room), we use Eq. (9.5):

$$L_Q = \frac{\rho^2}{1 - \rho} \tag{9.5}$$

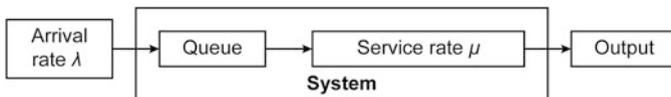


Fig. 9.2 Notations for queuing theory

The *length of the system* (e.g., the estimated number of patients in the waiting room *and* in the doctor's surgery) is determined with the help of Eq. (9.6):

$$L_s = L_Q + \rho = \frac{\rho}{1 - \rho} \quad (9.6)$$

Waiting time in the queue (e.g., time spent in the waiting room) can be found using Eq. (9.7):

$$T_Q = \frac{\rho^2}{\lambda \cdot (1 - \rho)} \quad (9.7)$$

Waiting time in the whole system (e.g., time spent in waiting room and doctor's surgery) is calculated with the help of Eq. (9.8):

$$T_s = T_Q + \frac{1}{\mu} = \frac{\rho}{\mu \cdot (1 - \rho)} \quad (9.8)$$

Task 9.1 Queuing Theory M/M/1 System

In a bookshop in the city centre there is only one cashier because the other two are off with influenza. Normally the cashier is able to cash up an average of 70 customers per hour. But on average there are only 55 customers per hour in the bookshop. Next to cashing up customers the cashier also has to unpack deliveries. Analyse the performance of the queue, and check if there is enough time to unpack deliveries.

$$\text{Inter - arrival time} = \frac{1}{55} = 0.018 \text{ h} = 1.08 \text{ min} = 64.8 \text{ s}$$

Every 65 s there is a new customer who wants to buy books.

$$\text{Service time} = \frac{1}{70} = 0.0143 \text{ h} = 0.86 \text{ min} = 51.4 \text{ s}$$

$$\frac{1}{70} = 0.86 \text{ min} \cdot 55 \text{ customers} = 47.3 \text{ min}$$

The cashier needs at average 51.5 s to cash up one customer and 47.3 min for all 55 customers per hour which means the cashier has 12.7 min per hour to unpack deliveries.

$$\rho = \frac{55}{70} = 78.6 \%$$

And so the cashier is occupied 78.6% of the time.

Now we want to analyse the queue as seen from the customer's perspective.

$$L_Q = \frac{0.786^2}{1 - 0.786} = 2.89; L_s = 2.89 + 0.786 = 3.68$$

There are on average around three people waiting in the queue and approximately four people in the system.

$$T_Q = \frac{0.786^2}{55 \cdot (1 - 0.786)} = 0.0525 \text{ h} = 3.15 \text{ min}$$

$$T_s = 0.0525 + \frac{1}{70} = 0.0668 \text{ h} = 4.01 \text{ min}$$

Customers are waiting 3.15 min on average in the queue and 4.01 min in the bookshop in total before they can leave the shop with their purchase.

Task 9.2 Queuing Theory M/M/c System

In the case of an M/M/c queue, formulas are different. We can find M/M/c queues for example in a distribution centre. There are several trucks waiting in waiting zones to unload their goods onto loading docks or to get loaded. In the case of M/M/c queues we have a Markovian distribution of arrival rate, an exponential distribution of service time and c servers (>1).

Consider the following example for M/M/c queues. On average there are 40 trucks arriving per hour and one loading dock is able to unload and load 12 trucks/h. Furthermore there are four loading docks. Assume that every loading dock has the same capacity and needs the same time. There is only one waiting queue.

To calculate the occupancy rate of the system we use Eq. (9.9):

$$\rho = \frac{\lambda}{c \cdot \mu} = \frac{40}{4 \cdot 12} = 83.3 \% \quad (9.9)$$

The distribution centre loading docks are occupied for 83.3% of the time.

To calculate the estimated number of trucks waiting in the queue we need to find the probability that the system is completely empty [Eq. (9.10)].

$$P_0 = \frac{1}{\sum_{i=0}^{c-1} \frac{(c\rho)^i}{i!} + \frac{(c\rho)^c}{c!} \cdot \frac{1}{(1-\rho)}} \quad (9.10)$$

$$P_0 = \frac{1}{\frac{(4 \cdot 0.833)^0}{0!} + \frac{(4 \cdot 0.833)^1}{1!} + \frac{(4 \cdot 0.833)^2}{2!} + \frac{(4 \cdot 0.833)^3}{3!} + \frac{(4 \cdot 0.833)^4}{4!} \cdot \frac{1}{(1 - 0.833)}} = 2.14 \%$$

The probability that the system is empty is 2.14%. Now it is possible to calculate the number of trucks in the queue [Eq. (9.11)].

$$L_Q = \frac{c^c \cdot \rho^{c+1}}{c! \cdot (1 - \rho)^2} \cdot P_0 = \frac{4^4 \cdot 0.833^{4+1}}{4! \cdot (1 - 0.833)^2} \cdot 0.0214 = 2.183 \quad (9.11)$$

In case of four loading docks and 40 estimated trucks per hour, 2.2 trucks are waiting in the queue.

The estimated number of trucks in the whole system is calculated using Eq. (9.12):

$$L_s = L_Q + c \cdot \rho = 2.183 + 4 \cdot 0.833 = 5.515 \quad (9.12)$$

On average there are 5.5 trucks in the system.

Waiting time in the queue is defined using Eq. (9.13):

$$T_Q = \frac{L_Q}{\lambda} = \frac{2.183}{40} = 0.0546 \text{ h} = 3.276 \text{ min} \quad (9.13)$$

Waiting time in the whole system is defined using Eq. (9.14):

$$T_s = T_Q + \frac{1}{\mu} = 0.0546 + \frac{1}{12} = 0.1379 \text{ h} = 8.274 \text{ min} \quad (9.14)$$

As you can see, waiting time in the system is 8.3 min.

9.3.2 Little's Law

In 1961, John D.C. Little provided the mathematical evidence for the rule that puts the inventory L (= average number of objects in a system) in relation to the throughput rate λ (= average arrival rate of objects) and the waiting time W (= average time an object spends in the system). Little's Law says "that, under steady state conditions, the average number of items in a queuing system equals the average rate at which items arrive multiplied by the average time that an item spends in the system." (Little and Graves 2008). Letting

L = average number of items in the queuing system (e.g., work-in-progress inventory in the system)

W = average waiting time in the system for an item

λ = average number of items arriving per unit time

the law can be represented as Eq. (9.15):

$$L = \lambda \cdot W \quad (9.15)$$

Little's Law demonstrates that when we reach a steady state, i.e., the system states are stationary and the arrival rate is smaller than the service rate (cf. Fig. 9.2), the average number of objects arriving in the system during a time period (e.g. 1 h or 1 day) are equal to the ones that are leaving the system during that time period. Elegant in its simplicity, Little's Law represents one of the basics in capacity

analysis. The following adapted example is related to the application of Little’s Law in a manufacturing plant described by Bozarth and Handfield (2013).

Consider an application of the Little’s Law to inventory and lead time analysis in a manufacturing system (Fig. 9.3).

The upper part of Fig. 9.3 presents the dynamics of incoming and outgoing orders in a manufacturing system. At point of time 1, two orders arrive in the system and the number of jobs in the system, i.e., the inventory $L(t)$ is 2 at $t = 1$. At $t = 2$, one more order arrives and first two orders are still processed. Therefore, $L(t) = 2$ at $t = 2$. At $t = 3$, two new orders arrive and the first order exit the system. Therefore, $L(t) = 4$ at $t = 3$. This inventory dynamics is shown in the bottom part of Fig. 9.3. Moreover, the upper part of Fig. 9.3. shows lead time ($s_j - c_j$) for each job, where s_j is the

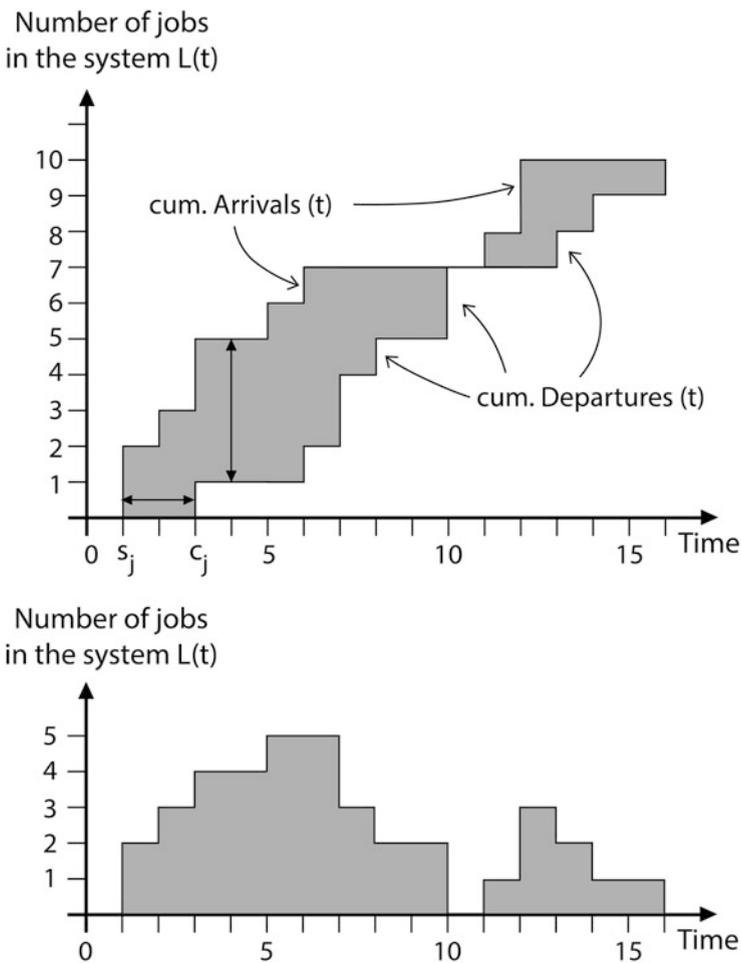


Fig. 9.3 Inventory and lead time dynamics analysis

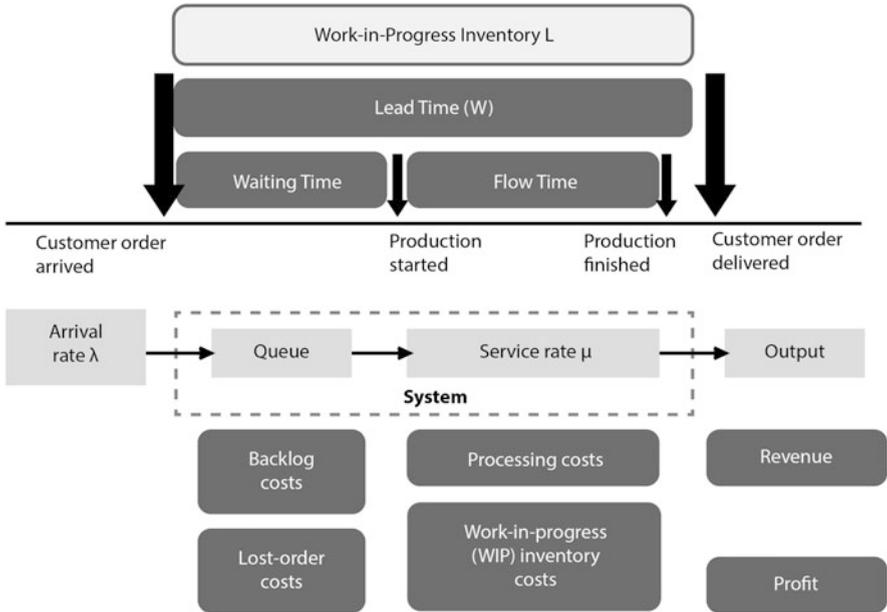


Fig. 9.4 Major components of the waiting line and Little's Law model

completion time of the job and c_j is the start time of job processing. For example, lead time for the job no. 1 is two time units.

Finally, we merge the previous discussions on the waiting line theory and the Little's Law (Fig. 9.4).

Four major events, i.e., arrival of a customer order in the manufacturing system queue, production start, production end, and the customer order delivery build the framework of the analysis. The time interval in between the first and the last event is called *lead time*. *Waiting time* is the time interval in between the first and the second event. *Flow time* is the time interval in between the second and the third event. During the waiting time, backlog costs and lost order costs occur. During the flow time, processing costs and WIP inventory costs is considered. The delivered orders generate revenues and profits.

Task 9.3 Little's Law

Let us assume that in a car garage, two standard repairs are offered in a special express service zone at extremely competitive prices. Batteries can be exchanged in workstation 1 and oil is changed in workstation 2. Prior to this, customers need to register and they also receive a general car inspection. Then they are assigned to either station 1 or 2 depending on the repair that is required (either battery or oil service). As shown in Fig. 9.5, 200 customers per day arrive at that garage.

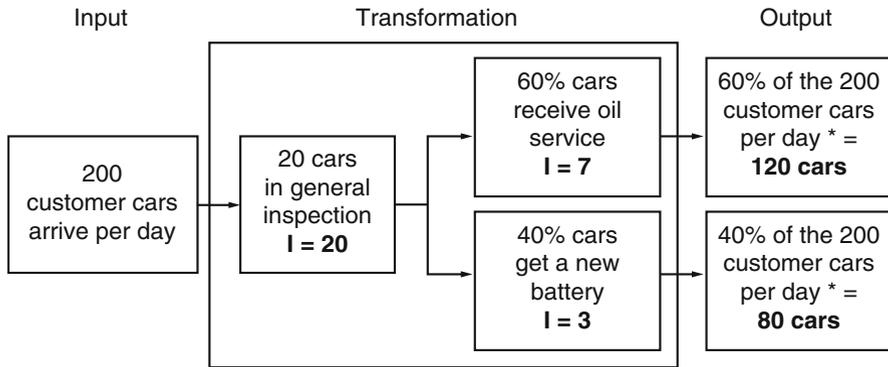


Fig. 9.5 Little’s Law—example of usage in a car garage

- As stated, all customers are passing through the general inspection where in average 20 cars are in the system for inspection.
- Sixty percent of clients request an oil service, and the average inventory is seven cars.
- The other 40% want their batteries to be exchanged, and the average inventory is three cars.

Looking at this scenario, we can calculate the following metrics:

The waiting time W for the general inspection is

$W = L/\lambda = (20 \text{ cars inventory in inspection}) / (200 \text{ customer cars per day}) = 0.1 \text{ day in general inspection} = 48 \text{ min waiting time, if we assume that the company operates 8 h (= 480 min) per day.}$

We can observe that 120 cars receive an oil service per day, and on average there are seven cars in the oil service area. Applying the same calculation principle as before, this leads us to the waiting time for the oil service of:

$W = L/\lambda = (7 \text{ cars inventory in oil service}) / (120 \text{ cars per day}) = 0.0583 \text{ per day} = 28 \text{ min waiting time for a day with 480 min working time.}$

But we also have a total of 80 cars per day that will receive a new battery. On average, there are just three cars in the inventory. Taking the formula according to Little’s Law, this leads us to the waiting time for the battery exchange of:

$W = L/\lambda = (3 \text{ cars inventory in oil service}) / (80 \text{ cars per day}) = 0.0375 \text{ per day} = 18 \text{ min of waiting time for a day with 480 min working time.}$

What is the waiting time for the cars receiving either an oil service or a new battery? In total, the cars require 48 min for the general inspection + 28 min for the oil service = 76 min of waiting time. In the case of the general inspection plus installation of a new battery, it is 48 min + 18 min = 66 min of waiting time.

As we have learned from that example, the simple but powerful “Little’s Law” formula can be used for just one single process, but can also be applied for a multi-process-step transformation system.

Learning take away on Little's law

One can also use that simple formula for the quick assessment of a manufacturing facility, for example in connection with a *rapid plant assessment* (RPA). During a plant tour, simply consider Eq. (9.15). If you ask during a visit to the factory what is the average throughput rate per day and what is the throughput time, you can simply calculate the average inventory that is carried. On the other hand, if you are an operations manager in a factory and you know Little's Law, you should try to identify the key drivers for the throughput time, i.e. the key processes with their durations that cause delays or prolong the throughput time. Try to understand these and try to identify actions to reduce these delaying factors. The overall idea is to keep the same output throughput rate, but to reduce the throughput time in order to bring down the inventory carried. If inventory is not a concern for the company, but the achievement of a higher output per day is the priority, a throughput time reduction will also help here. If inventory remains stable and throughput time can be reduced as a consequence, the throughput rate will increase. That means we can produce more, and that is the reason why Little's Law is also connected to management of capacity.

Discussion Points

- Where else could you think about applying the simple formula of "Little's Law"? Think about usage in a manufacturing environment but also in a service environment.
- Consider yourself being in the position of manager of an insurance company and you would like to increase customer satisfaction by promising to all customers that everyone would be served within 15 min of arrival. How could "Little's Law" help you?
- If you would like to increase performance of the value added system, thus reducing the throughput time, where would you prioritize your observations?

9.3.3 Bottleneck Analysis/Theory of Constraints

The *bottleneck* determines the capacity of the transformation system. To make it more transparent, just assume that there is a product (e.g. a chair) that requires for example four simple production steps (see Fig. 9.6):

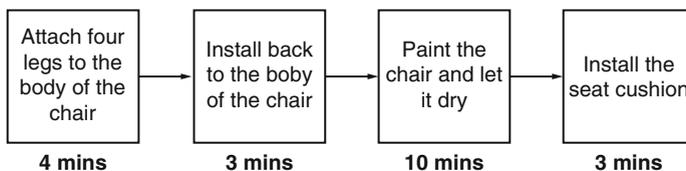


Fig. 9.6 Process chain

In this simplified production process, painting and drying requires the longest duration as it requires 10 min per chair (10 min per chair/60 min per hour = 0.167 h per chair). Or putting it more simply, six chairs per hour can be painted and thus the system capacity is six chairs as this is determined by the bottleneck. After the identification of the bottleneck (step 1), the operations manager's tasks would be to seek opportunities as to how this bottleneck time could be reduced.

Another frequently used term for bottleneck is *constraint*, as it is the process that prevents the enterprise from achieving its objectives (Goldratt 1990). If we want to produce ten chairs per hour, something needs to be done in order to limit the impact of that constraint or bottleneck, the performance manager needs to find a way (most probably with the help of a manufacturing engineer) to reduce the bottleneck time from 10 to just 6 min per chair. A possible solution might be to improve the spray process or to use a different type of paint or to increase the temperature for the paint to dry faster. That means a plan has to be created to mitigate the impact of the constraint and to reduce the bottleneck time (step 2). The operations manager and the manufacturing engineer are the dedicated resources that will need to work on the implementation of the identified measures (step 3).

Furthermore, one should try to better balance the work and maybe try to do some necessary preparatory work required for the painting, such as cleaning after the back of the body of the chair was installed. If this is also done, we are trying to spread the work from the bottleneck as well as to try to increase capability in related production processes (step 4). If this has been successfully implemented, the performance manager will start again to identify new constraints and bottlenecks as part of this continuous search for improvements (step 5).

9.3.4 Drum, Buffer, Rope

The drum is the instrument responsible for the *beat* (beat rate or *takt time*) of the production system. This can also be considered as the pace or production schedule and thus provides information regarding the items that need to be produced per time unit.

The buffer can also be considered as the *inventory* (or another type of resource) of the system which allows the bottleneck to perform at the beat of the drum. The last symbol is the rope. This is the means to exchange information or it enables necessary communication between the different parties. It refers to the need to synchronize the different elements or workstations in the system to operate in alignment and thus has the function of sending signals.

Assume there is a motorway that has five lanes and at a particular location (e.g., a bridge) it is narrowed to three lanes, then this is the capacity limitation or constraint, as cars could only use these three lanes. According to the theory of constraints (ToC), you only *achieve an improvement or advantage when it is possible to increase the capacity of the bottleneck*. That means for our example that you can only improve the system by creating a broader bridge with four or even five lanes.

The second principle of the ToC is that *it does not improve the performance of the system if you try to work on a non-bottleneck area*. For our example, if you create a better motorway with six lanes but you keep the old bridge with three lanes, this will not improve the system, as the bottleneck remains the same.

The third principle says that the *time that you spent at the bottleneck*, the bridge in our case, *is lost*. In real operations, you could try to mitigate the impact of the bottleneck by using well trained staff or by putting in a strict management system to lower the impact of the bottleneck. In a real factory the paint shop or a crane might be a bottleneck. In the case of the crane, you might schedule its usage tightly and should use a skilled crane operator who can maneuver goods with the highest precision, so that the time consumed for picking the goods, moving them and to position them at their destination is strictly limited.

We can summarize that bottleneck management and dealing with constraints is a daily task for operations managers. Furthermore, a constraint will always exist and due to expected or unexpected occurrences, new bottlenecks will arise (key people leave the company, workers are sick or on strike, a machine breaks down, a supplier cannot provide the parts. . .). Other drivers for bottlenecks could also be changing product mixes, usage of a new technology and the training of people to create new products using a new technology. Knowing and dealing with such constraints is part of the day-to-day business in SCOM.

9.3.5 Break-Even Analysis

In the previous sections dealing with Little's Law or the ToC, we looked only at capacity without consideration of profit and loss aspects. The break-even analysis is an approach that also looks at costs, respectively revenues. Slack et al. (2010) summarize that the break-even analysis is "the technique of comparing revenues and costs at increasing levels of output in order to establish the point at which revenue exceeds cost, that is, the point at which it 'breaks even'".

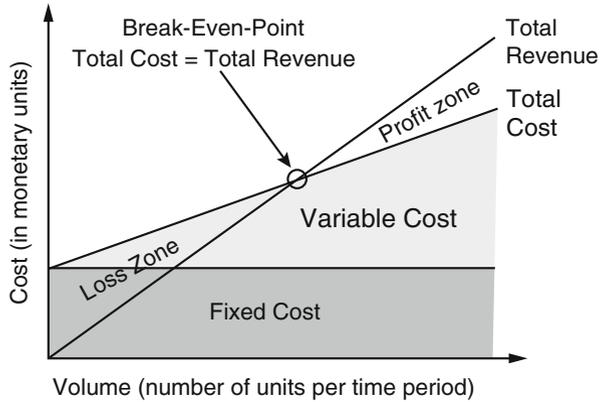
The *break-even point* is the point at which the total costs of the number of units that need to be produced are equal to the total revenues that are generated (Krajewski et al. 2013). That means that from a capacity point of view a firm needs to operate above the break-even point, or graphically speaking on the right-hand side of that point, as Fig. 9.7 depicts.

With the number of units that lead to a surplus on the revenue side, i.e., where the revenues are higher than the cost, the company will enter the profit zone. Below that production volume, graphically speaking, the firm is running left from the break-even point and thus is only generating losses, as the costs are higher than the revenues.

Task 9.4 Break-Even-Point

Put yourself in the position of a production manager who needs to evaluate if it is reasonable to purchase a new machine for the production of certain goods. The

Fig. 9.7 Break-Even-Point



underlying assumptions are that costs and revenues are linear functions and that we know these exact costs. Furthermore, interest rates or cost of inventory is excluded from our break-even analysis model. It will be your task to calculate the break-even point in the number of units but also in terms of money, i.e., in \$US.

Consider the following notations:

- BP_x represents the *break-even point in units x*
- $BP_{\$}$ represents the *break-even point in \$US*
- p represents the *price per unit*
- x represents the *number of units produced*
- vc represents the *variable costs*
- fc represents the *fixed costs*.

Equation (9.16) is used to determine the total revenues (TR):

$$TR = p \cdot x \tag{9.16}$$

Equation (9.17) is applied to determine the total cost (TC):

$$TC = fc + vc \cdot x \tag{9.17}$$

According to the definition of the break-even analysis, the *break-even point* is reached when TRs are equal to TC. That means for you as the production manager, you will need to set:

$TR = TC$ or considering the details from above we can use Eq. (9.18)

$$p \cdot x = fc + vc \cdot x \tag{9.18}$$

to identify the *break-even point in units*.

The *break-even point in units* thus equals [see Eq. (9.19)]:

$$BP_x = fc/(p - vc) \quad (9.19)$$

To convert this into monetary values (e.g. \$US), the result BP_x needs to be multiplied by the price per unit, i.e.

$$BP_{\$} = BP_x \cdot p = [fc/(p - vc)] \cdot p = fc \cdot p/(p - vc) \quad (9.20)$$

Based upon Eq. (9.20), the profit can also be calculated, because profit (simplified) equals $TR - TC$, which translates in Eq. (9.21):

$$\text{Profit } P = TR - TC = p \cdot x - (fc + vc \cdot x) \quad (9.21)$$

Consider a numerical example. You received the following annual values from your controlling department (see Table 9.2):

In order to calculate the break-even point in \$US $BP_{\$}$, you will need to use formula (9.6):

$$BP_{\$} = 20,000 \cdot 5/[5 - (1 + 2)] = 100,000/2 = 50,000\$/\text{year}.$$

That means the break-even point in \$US $BP_{\$}$ is reached, once the value of \$50,000 is exceeded. As a production manager, you would like to know the quantity in units that needs to be produced to reach the break-even point in units BP_x . Therefore you now need to use formula (9.18):

$$BP_x = 20,000/[5 - (1 + 2)] = 20,000/2 = 10,000 \text{ units}/\text{year}.$$

Of course, the break-even point in \$US is directly linked by the sales price per unit with the break-even point in units, as you can easily see in the example above. You can simply test the result by taking the BP_x (which is equal to 10,000 units in our task) and multiply it by the selling price (which is here equal to \$5/unit). The result is 10,000 units \cdot \$5/unit = \$50,000, as calculated above.

- **Practical Insights** In practice, the break-even point in \$US is more relevant for the sales or the controlling department, whereas the break-even point in units “talks” more appropriately to the managers responsible for production, purchasing or logistics. This is because of the fact that production or logistics managers need to consider not only the size or weight of the products in order to determine space requirements on the production floor or in the warehouse, but also to identify the correct lifting or transportation devices. That means that the break-even analysis is a simple calculation method that provides a rich variety of people inside the organization with information essential for their purposes.

Table 9.2 Initial data for break-even point analysis

Fixed cost (FC)	\$20,000
Material cost per unit	1 \$ per unit
Direct labour per unit	2 \$ per unit
Selling price per unit	5 \$ per unit

9.3.6 Decision Trees

In practice, *market uncertainty* and such factors as production cost, demand, prices, inflation or exchange rates influences managerial decisions. Should we expand our production or not, is it a profitable choice to redevelop the old distribution centre if demand for the following years is uncertain or should we sign the long-term contract with our supplier if we do not know if customers like our new product?

Decision tree analysis helps to make decisions in uncertain environments. A decision tree helps to build a graphic overview of possible strategies and to calculate in simple steps the revenue, cost and expected monetary value of several opportunities. Decision tree analysis offers a combination of strategic decisions, such as expanding a production site or not, and financial planning. It evaluates strategic decisions by its profitability to support the decision-making process. For that reason it can help to make decisions and aid design of processes and networks.

Task 9.5 Decision Tree Analysis

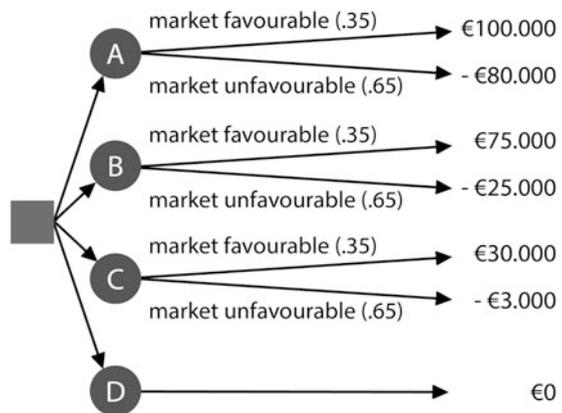
A company thinks about expanding their production site because they assume a favourable market development. To calculate *expected monetary value (EMV)* we have to consider probability P for both a favourable (0.35) and an unfavourable (0.65) market development. Option A means a large expansion, option B—a medium expansion, option C—a small expansion, and option D—no expansion. At the end of the tree you can see the cost or gain of each opportunity (Fig. 9.8)

To calculate the EMV we have to use Eq. (9.22):

$$EMV = P(\text{favorable}) \cdot \text{gain} + P(\text{infavorable}) \cdot \text{losses} \quad (9.22)$$

Using Eq. (9.22) it becomes possible to decide which expansion would be the most profitable:

Fig. 9.8 Decision tree expansion production site



$$\begin{aligned}
 EMV(A) &= 0.35 \cdot 100,000 \text{ €} + 0.65 \cdot (-80,000 \text{ €}) = -10,000 \text{ €} \\
 EMV(B) &= 0.35 \cdot 75,000 \text{ €} + 0.65 \cdot (-25,000 \text{ €}) = 10,000 \text{ €} \\
 EMV(C) &= 0.35 \cdot 30,000 \text{ €} + 0.65 \cdot (-3000 \text{ €}) = 8550 \text{ €} \\
 EMV(D) &= 0 \text{ €}
 \end{aligned}$$

We can observe that medium expansion would be the best decision from the financial point of view, in a case where market development will be similarly predicted. Option D, no expansion, would lead to no difference because the company would not be changing anything.

- **Practical Insights** It is important in decision tree analysis to identify all factors that influence cost and to decide which factors are uncertain in the calculation. The critical issue is how to assess probability for relevant uncertain factors and consider their influence. Moreover, a company should not focus only on financial analysis. Other factors may also be important and the financial part can only be a fraction of the decision-making process. In practice, decision tree analysis is frequently supported by the development of *business cases* for possible future expansion.

Discussion Questions

- Why do you think capacity management is important for globally active companies that have a large production network with multiple production sites?
- Why is capacity management very important from a strategic point of view?
- What are the consequences when it is identified that the existing capacity of a firm is too high as opposed to when it is too low? What are the corrective measures that you would suggest to adjust the existing available capacity so that it can meet future demand?
- Is it the right strategy to aim for almost 100% capacity utilization, or do you think one should also consider some idle capacity for the unpredictable?

9.3.7 Simulation: Case Study AnyLogic

Problem Description

Centrotherm Photovoltaics AG is a global supplier of technology and equipment for the photovoltaics, semiconductor and microelectronics industries. The company needed to identify the best automated production line and factory configuration to minimize costs and maximize throughput and reliability. Special focus was to:

- determine the type and amount of equipment required to fulfil production plans;
- evaluate layout alternatives to improve the throughput and utilization rate;
- inspect possible bottlenecks in the material flow;

- evaluate the impact of operator behaviour on factory output;
- test the consequences of maintenance within various time frames;
- identify system behaviour in case of breakdowns;
- identify scrap probability;
- evaluate change of performance during planned downtimes.

Model Development

The consultants used AnyLogic simulation and modelling technology to provide the answers to these problems. Using AnyLogic Professional's ability to create and save custom object libraries, the consultants encapsulated their vast simulation experience in the photovoltaic and semiconductor manufacturing industries and created their own libraries, which they reused in many projects, including this one.

Solution Development

These libraries featured elements built on top of the AnyLogic model development environment and allowed the consultants to easily model different kinds of equipment, material handling systems inside factories, personnel, and production control systems, all specific to the photovoltaic and semiconductor industries. In the Centrotherm project, this solution helped modellers quickly reproduce various aspects of the client's production system behaviour.

Testing the Solution

Once the model was built, the experimental phase of the project began. The consultants tested many parameters to find the best solutions. The input data, which included layout configurations and various parameters, was taken directly from Excel and Access files. Each simulation run reproduced 1 year of factory operation.

First, the consultants experimented with the overall production line design, using parameter variation and optimization. They tested many parameters, including those concerning capacity and the number of various pieces of equipment, cassettes, bins, etc., to see which configurations would work best in terms of throughput, reliability and scrap rate. Then the consultants worked to optimize transportation policies, buffer zone allocation, and watermark control processes.

Analysing the Results

Some of the proposed layout variants were rejected during this stage due to their poor performance. Finally, the few resulting solutions were tested manually to investigate the benefits and drawbacks of each one, and to find out how they could be further improved.

Implementation

The solutions proposed provided Centrotherm Photovoltaics AG with the opportunity to significantly improve the production line design and choose the best solution in terms of throughput, reliability and scrap rate at a low cost. Additionally, at the end of the project, the model was released to the client so that it could be used for

analysis of future changes in the factory. The model allows the customer to carry out their own experiments, playing with parameters and layout, changing input data, etc. This manufacturing facility simulation model will serve as a decision support tool at the factory for a long time to come.

9.4 Process Flow Structures

It is intuitively clear that not all products are produced in the same way. In order to enlarge on this for you, we need to think through another hypothetical case, in which you would be the producer and the product would be a chair. It is a very simple example, but makes it easy to grasp the underlying ideas and concepts.

9.4.1 Job Shop

Just put yourself into the situation that you plan to produce your own little chair for your room or for your apartment. You would go to the closest do-it-yourself centre, would buy some pieces of wood, some nails and your favourite colour of paint (e.g. red). These are the materials you would need for the chair. Furthermore, you need some tools, maybe a brush, a saw and a hammer. These standard tools and your materials plus your creativity and manual work are everything that you require in order to build your own, fully individualized piece of furniture (maybe you would produce and assemble it in your kitchen or in the garage).

The result would be an absolutely unique product and nobody else would have the same one! Maybe one of your friends will ask you to produce a second one, but with some changes regarding the size and also regarding the colour (your friend wants to have a bigger chair, painted in green). With your equipment, you would also be able to create such a product for your friend.

What we have just described is a typical set-up of the so-called “*job shop*” process flow structure. The secret behind it is that with such a process flow structure, absolutely unique products are made under the usage of standard tools in very low quantities. Also, the manual effort is quite high, in respect of the automation level, which is in general very low.

As you produced it manually and bought only a small amount of material, the unit price is quite high, but so is the flexibility to adjust your production set-up and to meet changing requirements. If you followed carefully the hypothetical wooden chair example from above, you will now understand that a job shop is a process flow structure that is used in order to create products at very low volume (just this one chair for you and the adjusted one for your friend). At the same time, we can understand that the job shop is suitable for creating products with great variation.

It is obvious that, even with this very unusual and hypothetical example, we still have developed the concept of the “*job shop*”. In reality, this is used for the creation

of e.g. replacement teeth, medical eye-glasses or maybe exclusively styled motorcycles or exclusively tuned cars. Another example is the traditional tailor who produces a dress or suit exclusively for you. These are all individual products with great variety and very low volume.

9.4.2 Batch Shop

Now let us continue with the hypothetical example of our chair, made out of wood. Let us assume that you would go to a market in order to sell your products. While you are selling and people come to you stating that they would like to have the small chair and the big one with arm rests in various colours, the result would be increasing the volume of similar types of products that need to be created.

Most probably, the best idea would be that you would offer two standard chairs (a small one and a big one) that could be painted in five different colours, for example. Because of that selected product portfolio, the natural reaction would be that you would produce a certain lot size of the small and then another lot size of the bigger one. As products are processed in *lots or batches*, this flow structure is called batch processing or batch production (i.e., products are produced in a batch shop). In the last production step, you would then do the customization, i.e., the individual painting on the market using a spray can.

Again, right now let us switch back to reality. Of course, not only exclusive suits are produced as you know, but also other exclusive products in small series like agricultural or construction machines respectively, helicopters or ambulances. In these cases, batches of similar products would be created. For example, the producer of special construction equipment would produce a small series of 20 excavators, which would all have the same communication equipment on board and would all be painted in blue for a specific customer and bearing the company's logo. The idea is to reduce the impact of set-up times and set-up cost and also to introduce stability into the value creation process.

9.4.3 Assembly Line

Let us continue the hypothetical chair journey. Your chairs are superb, everyone in your neighbourhood loves them and now even shops ask you to produce them in higher quantities. That means the required volume is significantly increasing and the consequence is, that for example manually cutting the wood for the chairs and running a manual assembly would no longer be efficient.

The consequence then might be to look at the possible usage of more machines for cutting the wood, drilling holes, putting the parts together, painting and even packaging them. So we would consider higher machine utilization and even think about more automation. Furthermore, we would think about the definition of work

packages or focus on work specialization (cutting, drilling...), leading to the identification of work stations in the *value creation process*. In order to ensure the constant *product flow*, the different stations would also need to be balanced to avoid *idle times*. The product being created moves at a defined *takt time* from station to station. This is also referred to as the product following a defined *pacing* through the work stations. In an ideal case, one would employ a *conveyor belt* or similar for the movement of the product throughout the production facility.

And this is what is applied in the real world. *Assembly lines* are used for mass production of articles with relatively high volumes and a well defined level of variants. The most known examples of products created on an assembly line are cars (e.g., Henry Ford's assembly line for mass produced automobiles of the famous T-Model). Other examples produced on assembly lines are household devices such as washing machines, refrigerators or microwave ovens, but also consumer goods electronics like TVs or computers. All these have in common that the item produced is made in *large volume* and is moving at a constant speed through the factory from work station to *work station*. This makes the production quite efficient, but it is also vulnerable if a station may not be working or the wrong (or no) parts have been supplied to the station. The result could be a stopping line.

Task 9.6 Assembly Line Balancing

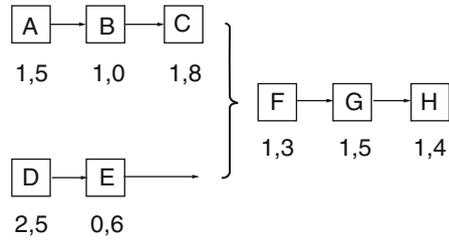
The planner in charge of assembly line balancing requires some inputs. One fundamental input is the manufacturing bill of materials (BoM) that provides the necessary information regarding the composition of the single parts that will be assembled in order to create the final product. To ensure this, the logical sequence of the different steps (so called *precedence relation*) also needs to be known (just imagine the sequence in which a pizza is created: first comes the dough, then the tomato sauce, followed by mushrooms, then the cheese, then it is placed in the oven, etc.). Additionally, the *task times* for different activities have to be known along with demand and available capacity per period of time.

Let us look at the example of how to assemble a simple manual scooter. You are in charge of balancing the assembly line according to the following inputs from the manufacturing engineers (Table 9.3):

Table 9.3 Initial data for assembly line balancing

Activity	Task	Predecessor	Task time (min)
A	Install brake in board	None	1.5
B	Install rear wheel in board	A	1.0
C	Glue anti-slip covering on top of the board	B	1.8
D	Pre-assemble Front Fork-Module	None	2.5
E	Install Front wheel in Fork-Module	D	0.6
F	Insert Front Fork-Module into Board	C, E	1.3
G	Install Steering Bar-Module	F	1.5
H	Test the correct functionality	G	1.4
	Sum of total Task Times		11.6

Fig. 9.9 Precedence diagram for the scooter assembly



Step 1: Precedence Diagram

The first step is to create the so-called “precedence diagram” based upon the inputs received. Table 9.3 indicates the precedence relationships and the corresponding diagram can be created. A simplified illustration is shown in Fig. 9.9:

Step 2: Identify the Number of Followers

According to the precedence diagram, we can identify the number of the following activities. Just count the respective following tasks. This is needed to apply heuristics for the later assignment of the tasks to workstations (WS).

- Activity A has 5 followers.
- Activities B and D have 4 followers.
- Activities C and E have 3 followers.
- Activity F has 2 followers.
- Activity G has 1 follower.
- Activity H has 0 followers.

Step 3 Defining the Assignment Heuristic

We will apply the heuristic to start the loading of the assembly line beginning with the activity that has the highest number of the following activities. The precedence diagram needs to be respected. If there are activities that have the same number of the followers, the one with the higher number of task times will be used.

► **Practical Insights** Heuristics can be applied to obtain a reasonable result, but sometimes it might be required to review and re-do the exercise in case that the heuristic might not lead to a satisfactory result. In addition to the heuristic presented here (Jacobs and Aquilano 2014), Heizer and Render (2014) suggest further heuristics, but these are not considered for our example. In real business, more sophisticated mathematical methods are used which are supported by software. These methods allow considering different cases with parallel machines, uncertain processing times, etc. (Dolgui and Proth 2010)

Step 4: Identify the Bottleneck Activity and Determine Maximal Production Rate

In our example, the activity “D” has the longest processing time of 2.5 min. This activity is also considered as the bottleneck and determines maximal production rate.

Let's assume that we work 8 h per day in our scooter manufacturing facility. Considering 60 min per hour, we get

$$\text{available production time per day of } 8 \text{ h/day} \times 60 \text{ min/h} = 480 \text{ min/day}$$

In order to identify maximal production rate per day, we need to divide the available production time per day by the bottleneck time. In our example, this is calculated as follows

$$\text{Max. production rate} = (480 \text{ min /day}) / (2.5 \text{ min /product}) = 192 \text{ products/day}$$

Step 5: Calculate the Takt Time Based on the Required Output

Let's assume, that we have to balance our assembly line for a production rate per day of 150 scooters. In this case, we need to divide the available production time per day by the required output. We get:

$$\text{Takt time} = (480 \text{ min /day}) / (150 \text{ scooters/day}) = 3.2 \text{ min /scooter}$$

Step 6: Calculate Theoretical Minimal Number of Workstations

As it can be observed from Table 9.3, the sum of the task times equals 11.6 min. Takt time is 3.2 min/scooter. That means we need to distribute the total task time over several workstations. This is exactly the task right now. In order to identify the minimum number of WS, we divide the total task time by the identified takt time:

$$\text{Min number of WS} = (11.6 \text{ min /scooter}) / (3.2 \text{ min /scooter/WS}) = 3.63 \text{ WS}$$

As we cannot have fragments of WS, we need to round up. That means for our example that at least four WSs will need to be considered.

Step 7: Loading the Workstations According to Step 3

Workstation 1

$$3.2 \text{ min} - \text{A (1.5 min)} = 1.7 \text{ min}$$

$$1.7 \text{ min} - \text{B (1.0 min)} = 0.7 \text{ min (= remaining idle time)}$$

Workstation 2

$$3.2 \text{ min} - \text{D (2.5 min)} = 0.7 \text{ min}$$

$$0.7 \text{ min} - \text{E (0.6 min)} = 0.1 \text{ min (= remaining idle time)}$$

Workstation 3

$$3.2 \text{ min} - \text{C (1.8 min)} = 1.4 \text{ min}$$

$$1.4 \text{ min} - \text{F (1.3 min)} = 0.1 \text{ min (= remaining idle time)}$$

Workstation 4

$$3.2 \text{ min} - \text{G (1.5 min)} = 1.7 \text{ min}$$

$$1.7 \text{ min} - \text{H (1.4 min)} = 0.3 \text{ min (= remaining idle time)}$$

The clustering of the activities per workstations (WS) is shown in Fig. 9.10.

Figure 9.11 illustrates the clustering of the tasks per workstations well, but it does not provide a good overview on the takt time and efficiency of the assembly line. Therefore, *stacked bar charts* are used in practice which demonstrate the loading per station including the corresponding idle time. In Fig. 9.11, the corresponding stacked bar chart is presented. In practice this is also called *Yamazumi chart* (“Yama” means *mountain* and “zumi” means to *pile up* in Japanese). Thus it is a graphical interpretation of the piled up work per station.

Step 8: Calculate the Efficiency of the Assembly Line

In the last step, the efficiency of the newly balanced assembly line will need to be determined. As the stacked bar chart (Yamazumi) shows (Fig. 9.9), there are idle

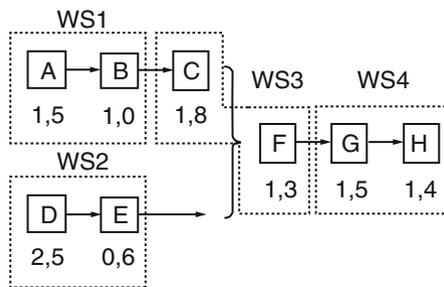


Fig. 9.10 Precedence diagram with indication of workstations

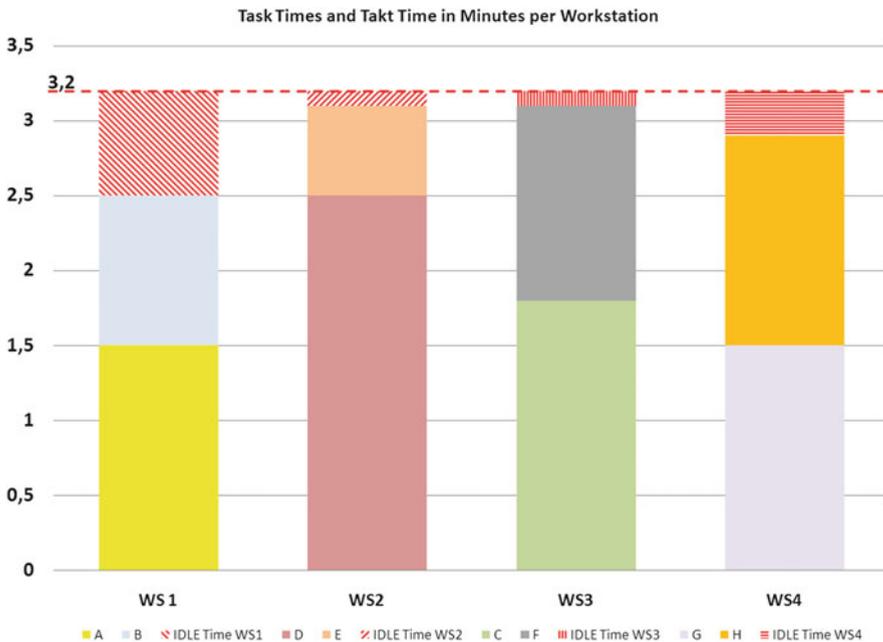


Fig. 9.11 Yamazumi Chart for the balanced assembly line

times on each of the WSs, which results in inefficiency. The planners of the assembly line will try to find the ways to reduce these inefficiencies in numerous iterations. If we consider the loading of our assembly line for the scooters, we can calculate the efficiency using Eq. (9.23):

$$\text{Efficiency } [\%] = \text{total task times} / (\text{takt time} \cdot \text{number of workstations}) \quad (9.23)$$

For our example, efficiency $[\%] = 11.6 \text{ min} / (3.2 \text{ min} \times 4) = 11.6 \text{ min} / 12.8 \text{ min} = 0.906$ which means 91%.

The planners would now try to break down the individual tasks into smaller portions in order to reduce the idle times and increase efficiency.

9.4.4 Continuous Flow

Now should demand for chairs be very high, i.e., many thousand items per day required, one would even rethink the chair's design and materials. The questions are how could we simplify the design in order to reduce the number of parts and as well as the *throughput time* of assembly? That means, one could argue, that the product should no longer be made out of wood, but maybe out of plastics. Instead of cutting pieces of wood, putting them together on the assembly line and then painting them, one could suggest that the chair is done in one continuous outflow of plastics in various colours. Production would take place following the plastics moulding process.

Instead of having multiple workstations, the process would take place in one continuous flow, a value-added process starting with the filling of the plastics granulate, heating it up, pressing it into the form required, cooling it and then removing it from the mould. Human intervention would be involved for supervision of the machines and to ensure quality, but creation of the product would be achieved through utilization of machines, using the highest automation. The cost per product would remain relatively low, but on the other hand, the cost for the facility and machines would be very high, because of the enormously high level of automation. Furthermore, complete customization is not possible because the moulds are especially designed to create one product and thus are very expensive. This will result in very low flexibility for adjusting the product to possible changes from the customer side.

9.4.5 Product-Process Matrix

In essence, the considered product flow structures have different advantages as well as disadvantages. The relationship between products and processes can be summarized in the form of a so-called *product-process matrix* (see Fig. 9.12).

Let us get back to the initial hypothetical example of our chair. If you want to produce your chair exclusively and in small quantities, you will select the job shop; if on the other hand the task is to produce the chair in the highest quantities, the

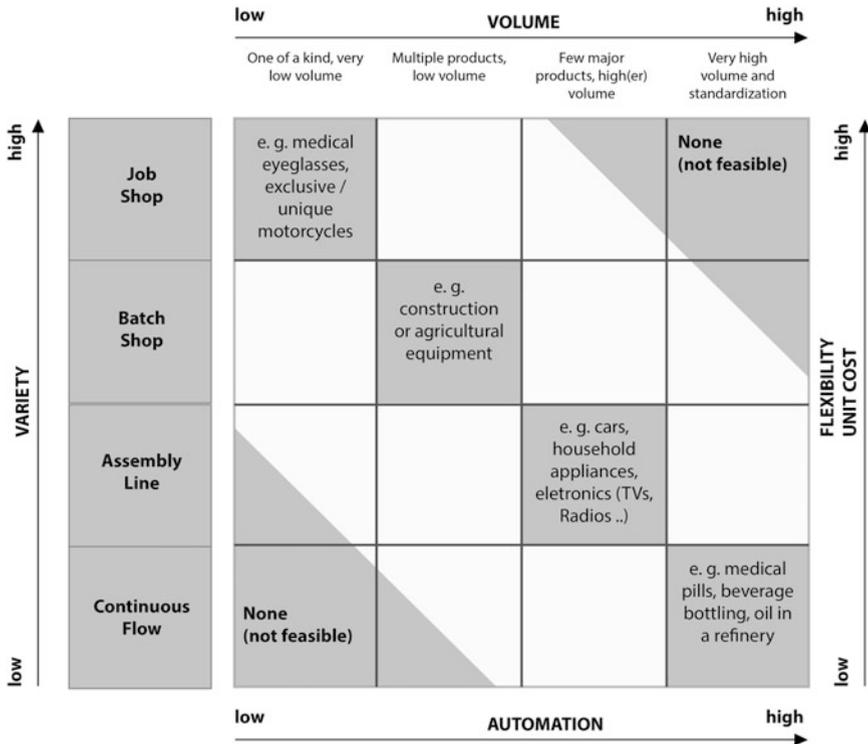


Fig. 9.12 Product-process matrix [based on Chase et al. (2006)]

continuous flow would be a recommended structure. Overall, the question of volume and variety are the factors that will drive your decision towards the most appropriate process flow structure.

9.5 Lean Production Systems

9.5.1 Lean Thinking

“Lean” means the continuous process of increasing efficiency and improvements in the organization, which requires teamwork, respect and taking over responsibility. Team members are also responsible for detecting defects and striving for their root cause, plus identifying a solution for future avoidance. Lean also requires a good relationship with the unions accompanied by the trust.

The lean organization is characterized by a set of the following five key principles (Womack and Jones 1996; Bicheno and Holweg 2008):

- *value* from the customer point of view
- *value stream* and waste (“*muda*”) elimination
- smooth *flow* throughput in production
- *pull-control* policies, e.g., *Kanban*
- perfection and *continuous improvement (Kaizen)*.

The underlying philosophy of all above mentioned principles is the *respect* for people and *learning* from mistakes.

9.5.1.1 Value

Identifying the ‘*value*’ of a product or service means understanding and specifying what the customer is expecting to receive. Understanding what the customer wants and does not want are key aspects in lean thinking. Womack and Jones (2005) described value as a capability provided for a customer at the right time at an appropriate price, as defined in each case by the customer.

9.5.1.2 Value Stream and Value Stream Mapping

The *value stream* presents the specific activities required to design, order and provide a specific product, from concept to launch, order to delivery, raw materials into the hands of the customer. The most effective process is achieved by performing the minimal required number of value-added steps and no waste steps. This is the ideal goal that is almost impossible to achieve in practice. A method to maximize the volume of the value-added steps in lean practice is called value stream mapping and analysis.

VSA (*value stream analysis*) is a tool to connect process flow and costs analysis. It is a suitable tool for redesigning the value creation systems. The availability of a well-trained team is essential as a key success factor. In VSA, different process steps in the value creation process are identified, listed, sequenced and visualized. Then the value-added times are measured. For comparison the non-value added times are also measured.

Value stream mapping (VSM) provides understanding of the current process by:

- visualizing multiple process levels
- highlighting waste and its sources,
- rendering “hidden” decision points apparent.

VSM also provides a communication tool for stimulating ideas by capturing critical organizational knowledge and identifying locations for data gathering and process measurement.

9.5.1.3 Flow

Womack and Jones (2005) described *flow* as “the progressive achievement of tasks along the value stream so that a product proceeds from design to launch, order to delivery, and raw materials into the hands of the customer with no stoppages, scrap or backflows”. The concept of flow is focused on the movement and value adding

processes of the product as such but also involves the material, information and financial flow. The flow principle can also be extended to the non-production area where it is related to information flow. The flow of information among the parties involved in a value creation network is as important as the physical flow of the materials.

9.5.1.4 Pull

The “*pull*” principle considers a system from downstream to upstream activities in which nothing is produced by the upstream supplier until the downstream customer signals a need. Pull means that one should start the creation of a product or service when the customer asks for it.

9.5.1.5 Seek Perfection

Seeking perfection is the element of *continuous improvement* in the lean philosophy. Perfection does not only mean quality. Perfection should be considered as being able to create exactly what the customer wants, when it is needed and at an acceptable, fair price with a minimum of waste. It is important to understand that a process will not be perfect and that there is a need for continuous re-examination of the process to remain competitive and lean. It is required to repeat this optimization cycle to get closer to the optimum with every loop taken. Womack and Jones (2005) summarized perfection as “the complete elimination of *muda* so that all activities along the value stream create value”.

9.5.2 Lean Production Principles

For an all-embracing view on the origin of Lean, please consider “The Machine that Changed the World” by Womack et al. (2007). Insights on the important Just-in-Time (JIT) principle are provided in Sect. 5.3.3 and various practical Lean shop-floor examples are presented in Sect. 10.2.

In 1950, Eiji Toyoda, a member of the Toyoda family who founded the Toyota Motor Company, visited Ford’s Rouge factory in Detroit. From 1937 to 1950, i.e. over a period of 13 years, Toyota produced in total 2685 cars in contrast to 7000 automobiles that Ford produced at the Rouge site in a single day (Womack et al. 1990). Eiji Toyoda assessed in detail the mass production principles applied in Detroit and concluded that the performance of the Toyota facilities could also be improved and he exchanged information on that with Taiichi Ohno, Toyota’s leading production engineer in Nagoya. Even the Japanese considered the Toyota staff as “a bunch of farmers”, initially producing looms, then military trucks and some hand-crafted automobiles—but today, the company is recognized as being one of the most efficient and highest-quality producers of motor vehicles in the world.

9.5.2.1 Lean Production/Toyota Production System

As a result of the research at the MIT International Motor Vehicle Program (IMVP) the expression ‘lean production’ was coined and Holweg (2007, p. 426) points out,

that: “The term ‘lean production’ was first used by Krafcik in 1988, and subsequently, Womack et al. of course used the term ‘lean production’ to contrast Toyota with the Western ‘mass production’ system in the ‘Machine’ book.”

Ohno (1988) identified that the U.S. mass production principles would not be applicable for the craft production oriented Japanese industry. Thus he created a new approach. In the western industries, multiple machines were used, and each one had to produce enormous amounts of the same pressed parts, as the changeover required specialists and took a lot of time.

Taiichi Ohno developed presses, in which the dies were slid in (every couple of hours instead of months) via rollers and fixed by simple quick mechanisms to use few machines to press with multiple dies. This saved *time, cost, and space*. Also instead of using specialist changeover teams, Taiichi Ohno suggested that the workers should be capable of and responsible for running the exchange of dies; after continuous efforts on improvement, changeover times were reduced down to just 3 min by the end of the 1950s. He also identified that it was more cost efficient to press small lot sizes of parts instead of running press batches of large quantities, resulting in (a) a reduction in carried inventories and (b) immediate identification of defective pressed metal sheets.

The result was an increased awareness regarding quality and early identification of flaws. It also avoided large quantities of wrongly produced parts that would have needed to be repaired, reworked or even scrapped—if they had followed the system of producing *large batches* according to the mass production philosophy. In order to further perfect this approach, no stupid exchangeable de-humanized workers would be required but instead a set of highly skilled, motivated and pro-active workforce!

Toyota also suffered from the financial crisis when it was subject to post-war American occupation. Toyota intended to lay off 25% of their workforce, which resulted in turmoil leading to the strengthened rights of employees and strong unions. The compromise was that the workforce was reduced by a quarter, but President Kiichiro Toyoda resigned and the remaining workers received a life-time working guarantee at Toyota accompanied by seniority-based wages and receipt of bonus payments. In other words, the *employees became part of the Toyota community* with the right to use the available facilities.

Ohno understood that because of this agreement, workers could remain at Toyota for life. Toyota and the workers became ‘one community’. So he intended to strive for *continuous improvement* of their skills and competencies as they became part of the “human assets”. This needs to be seen in contrast to Ford’s perception of using the workers as “human equipment” to perform one or two tasks repeatedly, supervised by a foreman, managed by industrial engineers and so on along the hierarchy. This also contributes to the establishment of a lean culture (Mann 2010).

One striking finding for Ohno was that in Ford’s approach, cars would be moved along the line, even when there were defects, because these were corrected in an especially dedicated rework area before being shipped to dealers. Back in Japan, Taiichi Ohno formed teams of skilled workers, led by a capable team leader. The team leader was manager and worker at the same time and was also utilized as a “jumper” to fill in the gap of an absent team colleague. These teams were

furthermore autonomously responsible for numerous assembly processes and for a certain area in the plant, so to say, their working domain. They were also responsible for quality control, housekeeping and cleaning as well as conducting small repairs. A key element of the teams was *continuous process optimization*—the teams were at the frontline, so they felt the pain and knew how to improve things.

9.5.2.2 Kaizen

This approach of *continuous improvement* is called “*Kaizen*” in Japanese (Imai 1993). MacDuffie et al. (1996) summarized that “under the philosophy of continuous improvement that characterized lean production, problems identified through the minimization of buffers are seen as opportunities for organizational learning”. In contrast to mass production in the western world, where mistakes or parts installed incorrectly would move throughout the entire line and by the time mistakes had possibly been identified, many faulty cars would have been created, Taiichi Ohno did something completely different. Ohno made another simple, but revolutionary, invention. He attached a cord to the assembly line and workers were encouraged to pull the cord, thus stopping the entire assembly line if a mistake was identified by a worker (Ohno 1988). Then the workers in their community looked for a solution to the problem, which gave them a lot of responsibility in making sure to do it right the first time.

9.5.2.3 Waste Reduction

In order to convert to lean principles in other functions of the organization, such a process can also be implemented in non-production processes: the cord or *andon*¹ sign is there to highlight mistakes when they appear (Dennis 2010).

Ohno also tried to assess the reason for mistakes occurring by asking the “Five Whys”, which is a structured approach to get to the so-called “root cause” of problems (Ohno 1988). Initially the assembly lines stopped very often, but the more mature this error analysis and prevention attitude became, the more failure rates dropped significantly to almost no defects: this is a 100% yield at Toyota compared to 90% in the mass production plants. This is the reason why in today’s Toyota plants there is almost no space planned for rework, because there is almost no rework compared to today’s mass production plants which devote 20% of their space to quality corrections. Close to the waste reduction idea is also the Six Sigma concept that set up special requirements on quality management and control (Chiarini 2012).

Waste, or *muda*, can be classified in two ways.

- Type I Muda is found in activities that add no value for the customer, but are necessary, to deliver the product.

¹Andon is Japanese and means “lantern” and thus is a visual, such as a traffic light that highlights in the production process anything going according to plan (green = OK) or if there are problems/disturbances (red = NOK) that would require immediate intervention and mitigation.

- Type II Muda is found in activities that do not create value and can be eliminated immediately, such as waiting and unnecessary transport.

Type I muda needs to be reduced to the minimum and type II muda needs to be eliminated.

This list of *7 + 1 wastes* is one of the key elements in Lean Thinking. Womack and Jones (2005) stated that Taiichi Ohno's original enumeration of the wastes was commonly found in production. The term "*seven plus one*" wastes comes from the fact that initially, seven wastes were identified, but then it became obvious that not meeting the requirements of the customer was also waste, hence "7 + 1":

- *Over-production* ahead of demand
- *Waiting* for the next processing step
- *Unnecessary transport* of materials (for example between villages, suppliers, facilities etc.)
- *Over-processing* of parts due to e.g. poor tool and/or product design
- *Inventory* that exceeds what is required
- *Unnecessary motion and movement* by the employees during the performance of their work (for example looking for parts, tools, documentation etc.)
- Production of *defective parts plus*
- *Not meeting customer requirements*

Recently, wasted *ideas or knowledge* waste has been added to "7 + 1" (Dennis 2010). The Toyota's case clearly demonstrates how aspects of the process flow structures, layout and factory planning and the evolution from craft to lean production are connected. Furthermore, it has shown that the principles of continuous improvement and thinking in terms of quality are all closely connected. It has also shown its initial limitations, for example the need for a total system view regarding the lean enterprise and the intensive need for cooperation with the SC partners involved (no matter if they are internal or external).

To summarize the principles of lean production, it can be stated that *lean* strives for the combination of the advantages of both craft and mass production, trying to avoid the high unit cost of craftsmanship and at the same time avoiding the rigid, boring and inflexible processes of mass production. This has led to the ability to reduce costs per unit and has dramatically improved quality while at the same time being able to provide a wider range of products to the customer and more challenging work for the staff. Regarding composition of workers' teams, lean production is striving for the creation of flexible teams consisting of multi-skilled staff that operates highly flexible machines to produce volumes of products in high variety. These principles are applied to the tiers of suppliers, but are also looking at an integration of dealers and buyers into the lean concept.

To summarize, the *Toyota Production System* covers in principle the following key areas (see also Heizer and Render 2014, p. 661):

1. *Pull-System*: Parts are only produced, when they are needed for further production. This is the contrary to a Push-System, in which material is fed into the

production area or warehouse. The purpose of the pull principle is, e.g., to increase efficiency and to avoid overproduction, unnecessary transportation and too high levels of inventory.

2. *Just in Time (JIT)*: Following the Pull-System, parts and modules are delivered to the station in the right quantity and at the right time (thus just in time), when they are needed. It is to avoid, that the facility is flooded with unnecessary material.
3. *Kanban*: Kanban means a “sign” or a “card”. A Kanban signal is used to indicate that a small batch of components needs to be produced. It is a practical approach based on real material consumption that initiates the replenishment process (unlike as material requirements planning (MRP) that presumes the planned replenishments).
4. *Standard Work Practices*: These are agreed upon documented procedures for the production process. This is to secure that everyone follows the same steps and sequence in the value creation. Thus, the timing per operation will be met and the quality to complete the work will be the same for all similar products.
5. *Minimal Machines*: Proprietary machines are designed for specific Toyota applications. It might also be a good idea to use general multi-purpose machines with certain adapters to simplify the usage and to ease the maintenance.
6. *Respect for People*: The employees are treated and are also respected as capable workers with knowledge and they are empowered to use their capabilities.
7. *Empowered employees*: The employees have responsibility. For example, they can stop the production in urgent cases, might evaluate improvement ideas and are also actively involved in quality control circles.
8. *Kaizen Area*: This is an area, where the employees are involved in order to make suggestions. Furthermore, the ideas or suggestions are tested, discussed and evaluated.
9. *Jidoka*: Machines are equipped with built-in devices for the monitoring of performance and to “make judgements”. If a problem occurs, the machine will interrupt the process, that’s why Jidoka is also considered as machines or automation with “human touch”. This avoids a processing of defective components and allows to analyse the root causes of the defects.
10. *Andon System*: Initially, in case of a problem a cord was pulled or a light was flashing at a station. Nowadays, problems are also openly displayed on a board or a screen in order to highlight deviations from the standard. It is part of the idea to visualize problems.
11. *Level schedules*: Models on the assembly line are mixed in order to meet customer demands and to avoid huge variation in the loading of the assembly line. The work needs to be balanced or levelled, focussing on the processing of smaller batches.
12. *Assembly components*: Parts or modules may be placed inside the car for an easier access instead of placing the parts in shelves next to the assembly line. Bigger modules are pre-assembled close to the main assembly line and are then fed into the main assembly line (“fishbone line feeding”).

9.5.3 Lean Supply Chain

9.5.3.1 Lean Thinking in the Supply Chain

Anker (2013) pointed out that a car can comprise 25,000 single parts and the related material cost represents approximately 70% of the total production cost. In relation to the price, the customer pays, the material cost accounts is in a range of 50%. The level of supplies provided by external parties is at approximately 75%, that means the in-house production roughly 25% (Anker 2013). In the case of the Smart production facility in Hambach (France), the external contribution is close to 90%, which shows that in that case the production depth is mainly with the suppliers and the original equipment manufacturer (OEM) accounts for approximately 10%.

If we compare this with the examples given earlier, Ford initially strived for 100% at the Rouge Complex, but reduced it back to 50% after World War II. For Taiichi Ohno the question was how suppliers and producers could in the efficient way work together in order to jointly reduce cost and increase quality.

The principle process from design to production in Ford's or GM's approach was that their own engineers designed the parts (previously purchased externally) completely on their own. Then the blueprints were sent to potential part suppliers who were supposed to submit their tenders. Following that, the supplier was selected in principle on price, but also considering quality and delivery reliability—with the side effect that suppliers were often switched, when others made better offers. Also here one can see the change in mindset regarding the criteria to select suppliers.

Lean SCM recognizes that there was a lack of cooperation from suppliers and their integration into the value chain. The potential of continuous improvement and their contribution regarding best practices remained unutilized in the mass production approach. Also suppliers followed the principle of producing large batch sizes that were shipped to the car producers. If a defect was discovered, many faulty parts had already been installed in cars and at the same time a high number of defective parts (inventory) were produced that required rework or scrapping.

Lean SCM identifies the potential of the suppliers that was—comparable to the knowledge capabilities of the shop floor workers—not utilized. Therefore lean SCM encourages suppliers to contribute their own expertise, meaning that Toyota specified the technical requirements that the part needed to fulfil, but the detailed design was developed by the suppliers (who were able to optimize the components they offered according to their own manufacturing).

Then, Ohno classified suppliers into multiple tiers. The *tier 1 suppliers* were the ones who autonomously developed parts based on key requirements (e.g. deceleration parameters, diameters and measures for brake systems. The suppliers created prototypes that became the serial components when they successfully passed functionality tests. The tier 1 suppliers were in principle not in competition with each other, thus they openly shared their information at supplier level. Taiichi Ohno also requested that the tier 1 suppliers should on their own establish a second line of suppliers for themselves according to a similar principle. These fabricating suppliers were in principle manufacturing specialists but not engineering experts.

These *second tier* suppliers were clustered and organized in non-competitor supplier associations which also contributed to openly sharing information among suppliers. As a side effect, “Toyota spun its in-house supply operations off into quasi-independent first-tier supplier companies in which Toyota retained a fraction of the equity and developed similar relationships with other suppliers who had been completely independent” (Womack et al. 2007, p. 60). Toyota also supported its suppliers with financial loans but also with workforce and encouraged the supplier base to offer their products to other companies and industries.

9.5.3.2 Kanban

Presently, Lean thinking in the SC has been frequently considered in light of SC risk management. It has been recognized that typical lean techniques such as single sourcing or low inventory make the SC fragile in the case of disruptions at factories and suppliers due to man-made and natural catastrophes (see Chap. 4, Ripple effect).

The next idea of the lean SCM is the simplification of the logistical processes and material call-offs. In principle, a connected chain as in a huge factory has to be created, in which the previous production process feeds material in limited quantities to the following process step after the material has been called off.

The idea was to employ *circulating containers or boxes*. Each container or box was equipped with a *card* which signals the need for another container or material. This card was called “*kanban*”. The containers and boxes were filled with parts and then sent to the next production step and—when completely empty—returned to their origin and thus acted as a call-off sign. The advantage was that inventory was reduced throughout this SC. In an unfavorable situation in which one container carried defective parts, the entire system would stop as soon as the defective part was detected, since the circulation of the boxes would also be interrupted.

In essence, the following five elements are crucial for a lean SC.

- *Perfect first-time quality* is achieved through the objective of creating zero defects, revealing and solving problems at their ultimate source (e.g. the shop floor), achieving higher quality and productivity simultaneously through teamwork or worker empowerment.
- *Waste minimization* is achieved by removing all non-value-added activities and by making the most efficient use of scarce resources (e.g. capital, people and space) and by applying JIT deliveries as well as eliminating any safety buffers for inventory reduction.
- *Continuous improvement* (reducing costs, improving quality and increasing productivity) is achieved through a dynamic process of change, simultaneous and integrated product/process development, rapid takt time and time-to-market, openness and information sharing.
- *Flexibility* is achieved through producing different mixes or greater diversity of products quickly, without sacrificing efficiency at lower volumes of production, through rapid set-up and manufacturing in small lot sizes.

- *Long-term relationships* between suppliers and primary producers (assemblers, system integrators) are established through collaborative risk sharing, cost sharing and information sharing arrangements.

9.6 Key Points and Discussion Questions

The decision on building a new or modifying an existing factory is of strategic importance and needs to contribute to the generation of competitive advantage. The role of factory planning is also to consider a successful partnership with the involved parties in the SC and it is also aiming at the efficient operations management. It is recommended to consider the following questions in factory planning activities in order to elaborate a successful approach to place a well operating facility with the appropriate process flow structures and capacity at the right location.

How to Plan a Factory in a Structured Way?

Factory planning is in general related to significant investments. That is the reason why the planning needs to take place in a structured and systematic way. A wrong approach can result in an enormous loss of capital. Thus, a logical connection between the initial planning phase of the facility, the realization of the new or adjusted factory and the later operation (running the factory) needs to be established. Between these different steps, careful milestone checks need to be made in order to obtain the approval by the decision makers to move into the next phase.

Which Different Options Could Be Considered?

In factory planning it is not always necessary to create a completely new facility. It is part of the general, regular tasks of the planners to re-design existing facilities in order to ensure that new models can be produced at existing sites. Furthermore, the existing plants can be expanded because of increasing demands. They can also be reduced (or even closed) when the markets show decreasing demands. Another option is the complete new creation of a factory on the “green field” to be close to the new market or local temporary production partnerships might also be an option to meet possible local content requirements.

How to Support the Factory Capacity Planning Process?

In order to ensure the appropriate output of the facility, the demand needs to be known or estimated in a substantiated way, so that the (design and effective) capacity can be determined. Useful tools that help to identify the capacity aspects are for example related to the application of Little’s Law, to run a bottleneck analysis (theory of constraints) or to apply the principles of a systematic break-even-analysis, decision trees, and waiting line theory.

What Are the Generic Process Flow Structures that Need to Be Considered?

When we talk about process flow design, the immediate relation to the aspect of volume of demand and the variety of the goods that will be produced needs to be

made. When products with very low volume and a significant variety have to be produced, the principle of the “job shop” will be the right decision. If products need to be produced in small lot sizes, for example 10 exactly same fire trucks for the regional fire brigade, these 10 products will most probably be produced following the “batch shop” approach, as these items are periodically produced in small batches or lots. Assuming that for example 700 cars or 2000 microwave ovens will need to be created per day, the “assembly line” is a suitable process flow structure as it allows mass production of standard goods following a regular pace while moving the item from work station to work station. Finally for the production of very large volumes of standard products such as medical pills, bottles of mineral water or sugar, the production following the concept of a “continuous flow” will be the fitting strategy.

How Do We Identify Non Value Adding Activities and What to Focus On?

One of the fundamental principles in running the operations is the application of the “lean thinking”. According the idea of “lean”, a clear statement of what the customer expects and what is considered as “value” is needed. Therefore, the value stream has to be mapped and value adding respectively non-value adding processes has to be analysed, so that unnecessary efforts or activities, such as waiting, over production, defects etc. can be identified. This results in the identification and elimination of the so-called 7 + 1 wastes. Recently also wasted talent or knowledge has been added to the 7 + x wastes. Another aspect of “lean” is the smooth flow of the value adding processes without obstacles or buffers according to the so-called “pull” principle. Lean thinking also emphasizes to seek perfection by continuous improvement. A fundamental lean consideration is the respect for people.

What Will Be Necessary for the Future?

Besides the focus on operational factors such as the design or the application of Lean principles, also the rapid development of intelligence and internet technology requires recognition. One modern trend is called Industry 4.0 which is related to the fourth industrial revolution following firstly mechanization, secondly electrification and thirdly the use of information technology in the production domain. Using the *Internet of Things*, machines and materials can exchange information in so-called cyber-physical-systems. It is expected to gain additional efficiency potentials of approximately 30% due to the intelligent combination of machines, materials and the human being (Lemmer 2014).

Discussion Points

- Discuss in groups which external factors might influence companies to search for new manufacturing or service sites
- Elaborate on the advantages and disadvantages but also which types of risks and opportunities you can see when firms are regularly adjusting their industrial footprint
- Analyse the impact of lean thinking on SC risk and vulnerability

- What are new requirements for the human being in the production environment considering the development towards Industry 4.0?
- Will the new additive manufacturing technologies such as 3D printing in combination with new lightweight materials such as carbon composites impact the process design and flows structures in future?

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