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**Managing logistic objectives in production with volatile demand
based on the example of company EXTREME-MET**

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Logistika ülesannete juhtimine tootmises muutliku nõudlusega EXTREME-MET ettevõtte näidise põhjal

Managing logistic objectives in production with volatile demand based on the example of company EXTREME-MET

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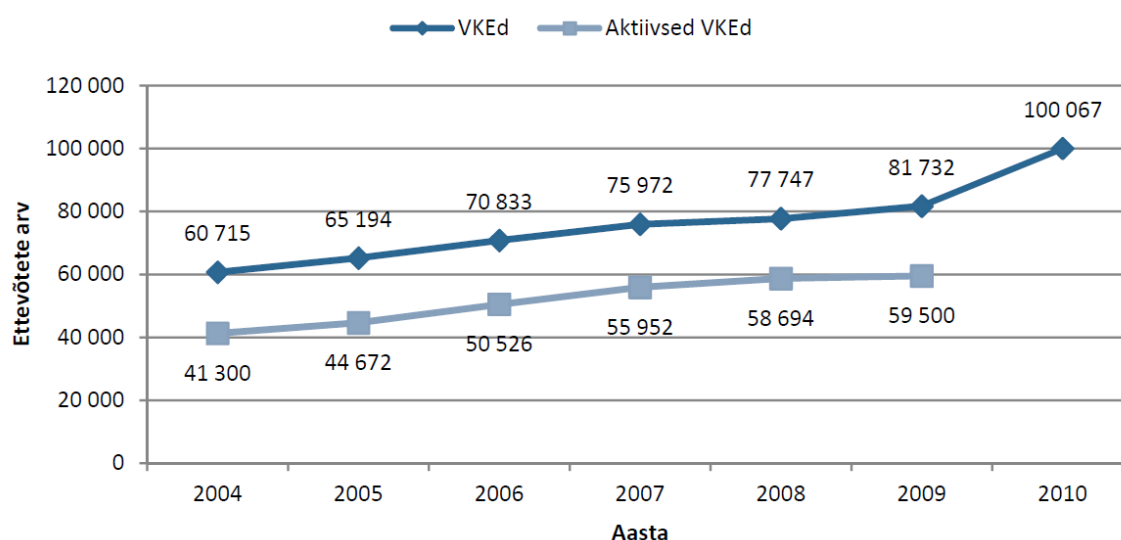
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Kokkuvõte

Firma üheks tähtsaimaks strateegiliseks eeliseks võib pidada hästi planeeritud tootmist. Selleks et edukalt toota, tuleb seda teha paindlikult, kergesti juhitavalt ja tellimused tuleb täita tootmisprotsessi käigus kavandatud ajaks. Kui eelnimetatud tingimused on täidetud, saab ettevõtte eelistuse konkurentide ees, kuid võidab ka klientide usalduse. Usaldav klient tuleb järgmine kord ettevõttesse tagasi.

2010. a uuringu põhjal on 99,8% Euroopa Liidu ettevõtteid väike- või keskmise suurusega ettevõtted. Eestis on neid lausa „99,9%“ [1, p 9]. Järelikult on väike- ja keskmise suurusega ettevõtted edukad, mis omakorda mõjub positiivselt kogu majandusele.

Väike- ja keskmise suurusega ettevõtted jagunevad aktiivseteks (üle ühe töötajaga ja kasumit tootvad) ja mitteaktiivseteks. Aktiivseid ettevõtteid on Eestis 73% (vaata Joonis 1).



Joonis 1. Aktiivsed ja mitteaktiivsed väike- ja keskmise suurusega ettevõtted aastatel 2005-2010 [1, p 9]

Väike- ja keskmise suurusega ettevõtete vaheline dilemma seisneb juba selles, et suurte investeeringute tegemine, nagu näiteks tootmise planeerimise programmi ostmine, on nende jaoks on küllaltki keeruline, kui võrrelda suurettevõtetega. Esmapilgul võib tunduda, et neile piisab ka lihtsamatest valemitest ning vahenditest, kuid praktika näitab, et mitte.

Aga praktika näitab, et see ikkagi ei piisa.

Uuringud näitavad, et väike- ja keskmise suurusega ettevõtete probleem seisneb järgmises: „Eesti ettevõtete hea tehnoloogiline tase, kuid madal seadmete kasutusefektiivsus“ [2, p

62]. Eelnimetatu tuleneb sellest, et tootmist planeeriti valesti või ei taganud kasutatud vahendid piisavalt efektiivset tootmist.

Selle lõputöö eesmärk on luua väikemetallitööstusettevõtte EXTREME-MET näitel tootmise planeerimis abistav vahend.

Tootmise planeerimise all on tuleb mõista ettevõtte sisemist logistikat ja see tegevuste kavandamist, näiteks tootmisele kuluv aeg, töö tootmisprotsessis tase (work in process, WIP) töökohal jne.

Tootmise planeerimise muudab keeruliseks see, et logistika eesmärgi saavutamiseks teostatavad tegevused on omavahel seotud ja samal ajal mõjutavad üksteist.

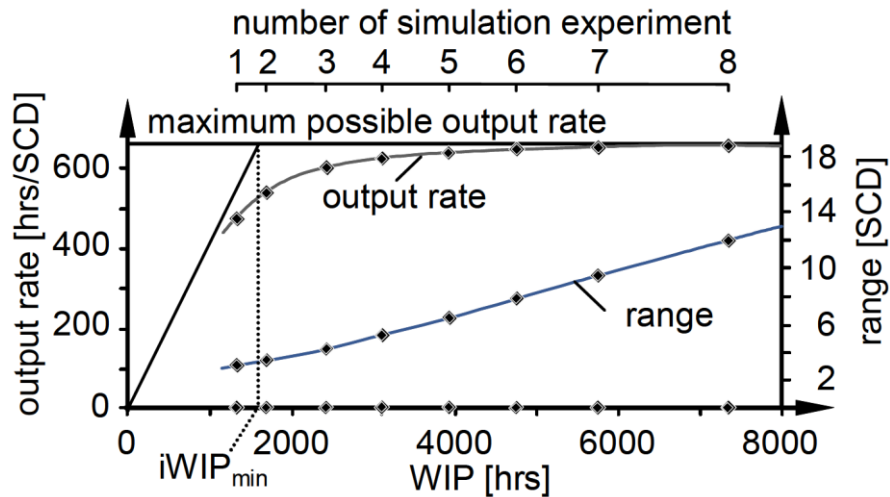
Tootmise planeerimise dilemma (scheduling dilemma [3, p 372]) seisneb selles, et selleks et millegi tootmiseks kulutada minimaalselt aega, tootmises tuleb olema väike töö tootmisprotsessis tase (kõrge töö tootmisprotsessis tase aegleb toodangu läbimise tootmise süsteemi läbi). Teiselt poolt, selleks et olemasolevat seadmestikku tootmises maksimaalselt koormata, peab töö tootmisprotsessis tase olema kõrgel tasemel. Tootmisprotsessi graafiku usaldusväärsuse tagamiseks tuleb toota võimalikult lühikese aja jooksul, kuid nagu ka eelpool kirjeldatud, see segab teisele ülesannete.

Iga ettevõtte peab ise otsustama, mis on nende jaoks oluline. Kas koormata kalleid seadmeid maksimaalselt, tagamaks nende kiire äratasumise aja, või ettevõtte jaoks on oluline, et nende tootmise oleks kiire, ja nende tootmise graafik oleks usaldusväärne.

Tootmise planeerimiseks kasutatakse mitu meetodit. Nendeks on arvutiprogrammid, järjekorra mudel (queuing model) ja logistiliste operatsioonide kõverad (logistic operating curves). Kolmandas peatükis on iga meetodit kirjeldatud. Lõputöö eesmärgi saavutamiseks kasutati logistiliste operatsioonide kõverad meetodit.

See tootmise andmete analüüsimise meetod on loodud Saksamaal Leibnizis Hannoveri Ülikoolis, kuid mis pole tänini väljaspool Saksamaad tuntuks saanud.

Joonisel 2 on kujutatud logistiliste operatsioonide kõverate näiteid. Jooniselt nähtub ühe töökoha dünaamika seisund sõltuvalt tellimuste arvust ja töö tootmisprotsessis tase. Punktirjoonega kujutatakse ideaalset tootmist seisund selle töökoha jaoks. Joonise järgi ei muutu toodangu koguarv ka tellimuste koguarvu suurenemisel.



Joonis 2. Logistiliste operatsioonide kõverate näidis [4]

Kui aga töökohale esitatakse vähem tellimusi, ei saa see töötada täiel võimsusel, mis omakorda tähendab, et selle töökohaga oleks võimalik toota rohkem toodangut.

Peatükkides 3, 4 ja 5 kirjeldatakse, mida on võimalik järeldada logistiliste operatsioonide kõveratest.

Logistiliste operatsioonide kõverate meetodite kasutamiseks tootmises on vaja kasutada tabelarvutusprogrammi (näiteks Microsoft Excel). Selle lahtritesse sisestatakse andmed, mille alusel arvutab programm vajalikke valemide kasutades välja logistiliste operatsioonide kõverad. Nendelt omakorda nähtub töökoha seisund.

Tegelikult, et kasutada logistika operatsioonide kõvera mudel, ettevõtte ei pea osta Exceli litsents. Internetist on võimalik leida vabavara OpenOffice. See tabeliarvutiprogramm võib avastada ka Microsoft Exceli failid ja selle tabelarvutusprogrammi abil saab luua vajaminevaid mudeleid ja neid välja arvutada.

Eeltoodust järeldub, et logistiliste operatsioonide kõverate mudeleid on võimalik välja arvutada täiesti tasuta, mis omakorda võimaldab planeerimise meetodit kasutada ka väike- ja keskmise suurusega ettevõtetel.

Introduction

One of the most important strategic advantages of a production company is the smoothly running production. The production that is flexible, easy to control and fulfils the tasks that were planned on time, will give the company the advantage over their competitions and will help to gain the customer's trust.

While speaking about the small and medium enterprises, it is especially important. Unlike big companies, small and medium enterprises have less space for making mistakes financial wise and less resources to experiment with their operations.

Another reason is that there are simply a lot of small and medium enterprises. Research shows that in European Union inside all companies, the percentage of small and medium enterprises is: "99,8%" [1, p 4], and for Estonia it is: "99,9%" [1, p 4].

The sheer amount of the small and medium enterprises shows that the influence on such companies can and will influence the whole economy of a country.

The problem that will be discussed inside this work is the planning of a small company production. It is done on the example of a metalworking company EXTREME-MET (see Figure 3).



Figure 3. The EXTREME-MET company logo [5]

EXTREME-MET work is project-based. Customers are coming to the company with their wishes and drawings, or with their orders and ideas. The company is able to produce products from metal, based on the drawing, or create a drawing for future product, based on the customer wishes.

They are procure-to-order or for some customers design-to-order type of company. It means that they are ordering the material only after getting the order.

The EXTREME-MET company operates under volatile demand. It means that the load on the production shifts all the time. The problem of the volatile demand through the supply chain is: "not only are retailers serving end consumers facing volatile demand, but this volatility is being passed on to manufacturers and distributors at different stages of the industry value chains" [6].

For the EXTREME-MET company there is time, when there is no orders, or short orders that are not using the full capacity of the production, then there are periods when there are big, complicated orders that need a lot of capacity, and the customer demand to do it as quick as possible. All this requires creating a production schedule as quick as possible. Even if it is estimated. Still, even at the beginning of the project negotiations, the estimated production period that this project will take is needed. The tool for planning the production can help for project managers to get this data quicker.

Today the production plan for EXTREME-MET is done with simple calculation (spreadsheets and calculator). The same is usually the case also for others small and medium enterprises.

In case of this approach, the production plan is no optimal for the company.

Big companies are using different scheduling and modelling software's to create the best possible production schedule for them. However, this software is an impossibly big investment for most small and medium enterprises. Another reason could be that the tool for production planning is considered as not important, because there is not a lot of workstations and one person can do the production plan.

From this comes the dilemma. On one hand, small and medium enterprises are very important for the economy, on the other hand, small and medium enterprises don't have the funds to buy for them the tools to make the business and production processes smoother. On one hand the amount of planning for the small and medium enterprises don't actually require such complicated tools as, for example, ERP (enterprise resource planning software), but it would have helped to optimize the company activities.

Many small and medium enterprises require a simple, but useful tool that will help to analyse the production and plan the resources usage in the best possible way for their company.

It this work will be analysed what kind of objectives should be paid attention to while planning the production (see chapter 1). The tools that are usually used for production planning will be shortly describes and one will be chosen for the EXTREME-MET production planning (see chapter 2). The tool will be applied and the schedule will be created, using the data that the company EXTREME-MET will provide for experimentation (see chapter 5).

In conclusion, there should be created a model to help a small production company to plan their production. And in the future, with this tool, the production manager should be able to see the state of their production with their current production plan, and then will be able to optimize their resources and capacity usage, according to their requirements and company strategy.

1. Logistic objectives today

Logistic importance to companies have significantly risen in recent years. With such popular production instruments as just-in-time, one-piece-flow, kanban, it becomes more important to manage the stock levels, be it internal or external.

If in the past, under logistics it was understood the movement of goods from point A to point B, now in XXI century, its role have shifted. It became a part of the system, that should minimize the usage of resources, save energy and be ecologically-friendly. Today there is many disciplines, which are dealing with logistical problems and many methodologies that put emphasis on its different aspects. Example of some are: green logistics, ecological logistics, reverse logistics, supply chain management and more.

However, not only are these disciplines dealing with logistic. Manufacturing and operation studies are also focusing on it. For example, lean manufacturing.

In today's world, everything is so interlinked, that one cannot be changed and analysed without another.

In this paper, the logistic is divided to external and internal. As the goal of the research is to create a tool that will enable the company to make the production scheduling easier, the research will be focused more on the internal logistic.

The idea for dividing the company's inventory to external and internal came from German author, Wiendahl (Figure 4). Also from Germany came the term 'production logistic', the main target of this methodology is: "the pursuance of greater delivery capability and reliability with the lowest possible logistic and production costs" [8, p 2].

Similar ideas could be found in, for example, American books, under the name of supply chain management, and it has similar description and goals: "coordinating or integrating a number of goods- and services-related activities among supply chain participants to improve operating efficiencies, quality and customer service among the collaborating organizations." [9, p 8].

	Logistic Performance	Logistic Costs
External	<i>make-to-order production</i> delivery time delivery date deviation delivery reliability	price
	<i>make-to-stock production</i> service level	
Internal	throughput time due date deviation due date reliability	inventory utilization costs of delays

Figure 4. Logistic performance and logistic cost objectives of internal and external logistic[7, p 20]

Different terms with similar meaning. Only in case of production logistics, the emphasis is more on logistic and operations management and control. In supply chain books, authors focus more on relationship management in supply chain (supplier-company-customer).

As the German idea to divide company inventory (and operations) to external and internal is quite simple and understandable, this chapter is constructed based on this classification.

External logistic is the one that the customer usually sees as a supplier's delivery time. The external logistic objectives are following (see Figure 4): delivery time, delivery date deviation, delivery reliability and service level.

Internal logistic is (see Figure 4): throughput time, due date deviation and due date reliability.

The better the external and internal logistic objectives performance is, the more advantage the company has over their competitors. In addition, important advantage is the costs. Internal logistic costs are mainly included inside the price of a product. Therefore, if the company lowers the costs, the price of the product will be lower, and it will gain advantage. Usually the cost of external logistic is not so high compared to internal, and it is easier to see and manage.

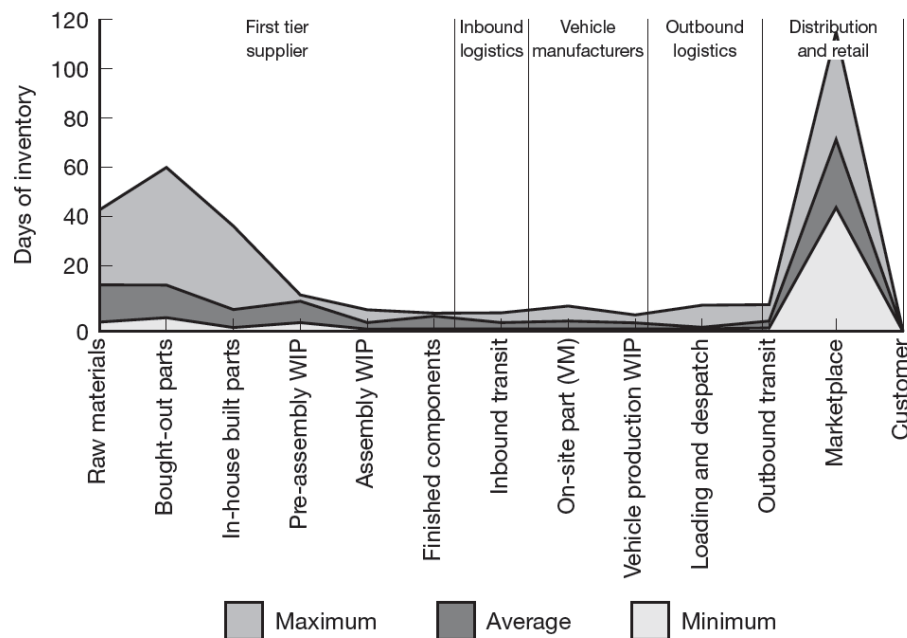
The trend for the future is 'doing more with less'. That means to reduce the costs, be more ecologically friendly and flexible, and use fewer resources. That also means the reductions

of inventory, both external and internal. One of the new strategies to do it is to outsource the inventory planning and storing. By doing it, the company can reduce the costs and human resource usage. The companies, who are doing such kind of work have their own strategy to deliver on time and reduce costs and there are allocating all their efforts to continuous improvement of their business. While manufacturing companies usually focuses more resources on their business-target processes, namely on product development and manufacturing.

The manufacturing processes and business process have undergone big changes in the late decades. And the changes are still continuing to occur.

1.1 External logistic and inventory

It is important to separate internal and internal inventory for management and analysis purposes. In a make-to-stock company the external stock is noticeably bigger than the internal stock (see Figure 5). In a company with make-to-order strategy, if the planned operations are healthy and work like planned, the situation is backwards, the finished products inventory is almost non-existing, and the raw material inventory is the highest point of inventory level.



Source: Holweg, M. and Pil, F.K., *The Second Century*, MIT Press, 2004

Figure 5. Inventory levels in automobile industry [10, p 21]

With purchase-to-order companies, inventory maximum is as high as the maximum of one order WIP levels. However, of course it will also depend on the raw materials lead time,

because the situation could be so, that some components that were delivered earlier are waiting for arrival of other components needed for production of one order.

1.1.1 Delivery time

Most companies usually measure delivery time from the moment that the order of a customer was created inside the company to the shipment time (the moment it was delivered to the customer). Usually the end-customer does not see from what steps consist the delivery time. If the company uses make-to-order operation model, the time it takes to assemble or produce the ordered product, is also included inside the delivery time. More complicated case (and more difficult for the company to manage and control) is when the company uses the procurement to order operation model (as in the EXTREME-MET company) that means that they are buying raw material from supplier only after receiving an order from their customer. This time then is also included inside the “delivery time”.

The delivery time objective have a very big strategic advantage. “enterprises with considerably shorter delivery times than the competition grow approximately three times faster than the market and yield double the profits” [7, p 21].

When the company chooses their supplier, nowadays the decisive factor becomes not only quality and price, but also the delivery time and delivery reliability (see Figure 6). In cases when these three factors are not superior to each other, the company needs to decide which is more important for them and exchange one for another. With some suppliers, it is possible to exchange the price for delivery time. It means that the shorter delivery time is possible with paying ‘surcharges’, additional payment for speed.

“Many transportation services offer various modal combinations, as well as warehousing and customs-clearing services” [9, p 19]. Today, with the just-in-time operating model, using transportation service or even warehouse service becomes the normal occurrence. Such companies provide to manufacturing or service firms the solutions with transportation, warehouse and also in some cases supply chain planning.

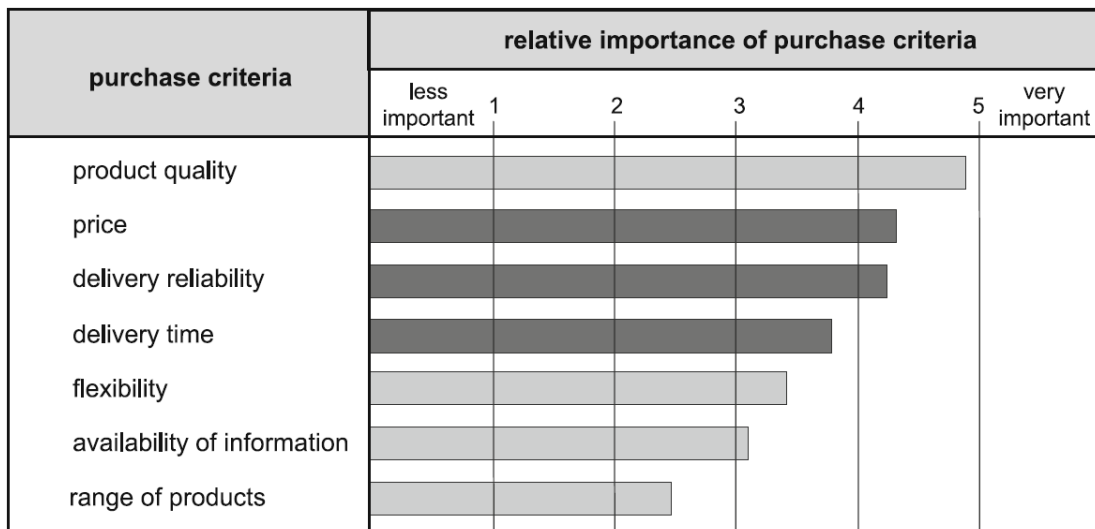


Figure 6. Criteria for purchasing products (Siemens Inc.) [8, p 2]

1.1.2 Delivery reliability and delivery date deviation

Delivery date deviations is a difference between planned delivery date and actual delivery date. Did the order arrived early or late? Today customers prefer to get their ordered products not later or earlier, but exactly on time.

Manufacturers, who prefer to operate with low inventory to save warehouse space, cannot storage the raw material, before the previous batch is used, and the space is freed. Also with this operation strategy, if the delivery is late, the production will be stopped due to raw material shortage. This is the reason, why companies are calculating delivery reliability of their supplier: “The *delivery reliability* refers to the percentage of orders delivered within a defined delivery reliability tolerance” [7, p 25].

With high delivery reliability (high percentage of orders delivered on time), the supplier will be more successful than their competitor, and will gain customers trust and as the result, their loyalty.

The delivery reliability starts from the reliable delivery date that was promised to the customer during the negotiation stage. However, it depends on how accurate and reliable is the estimation of times for order completion, and that includes the production schedule.

As more and more manufacturing companies integrate just-in-time manufacturing strategy, those companies can use only use suppliers, who have high delivery reliability. With unreliable supplier, companies are forced to create and increase their safety stock, which is an additional cost for them and defies the principles of just-in-time manufacturing.

1.1.3 Service level

The service level of external logistic is the most important point for companies, who are producing using make-to-stock operations model. Service level is measured in percentage of a satisfied demand. That means that it is calculated, how many orders the company could fulfil in a period of time.

If the order was not satisfied (due to a lack of stock, which means that the demand level in that period was higher than the capacity of a company), the customer will choose the competitor. The service level for make-to-stock companies is more important than delivery date deviation, but for make-to-order companies it is vice versa.

For make-to-stock production, there are two main dangers in production: inventory and utilization. If a company responds to increased demand and raises their stock level, it automatically will increase the inventory cost. The company can fulfil more orders, their service level has risen, but if demand rise was temporary, it can lead to losses.

A company with make-to-stock production is less flexible; they are usually producing with full utilization rate. If the capacity of their production rises, there is a danger of having lower utilization rate when the demand has decreased.

It is a careful balance of cost and profit. And according to Lödding “Many enterprises are not able to precisely measure the service level because they do not even compile the non-fulfilled demands” [7, p 29]. And with this loose opportunity to grow.

1.2 Internal logistic (or production logistic) and inventory

Many researchers in recent years have believed that the reduction of warehouses is the next step in manufacture companies evolution. But as the practice have shown, it is not entirely so, there are still warehouses (see Figure 5). What has changed is the warehouse management system (everything that could, became automated) and warehouse shapes.

Now there are build narrow and long warehouses with many entry points for trucks. That allows for the companies with high rate of inventory throughput to increase the incoming rate of materials. More trucks can come inside the warehouse and be processed, the queue have decreased.

Then there are big, high and fully automated warehouses, which do not require the human operators.

Another variety are warehouses with big number of products in small quantities.

1.2.1 Throughput time or lead time

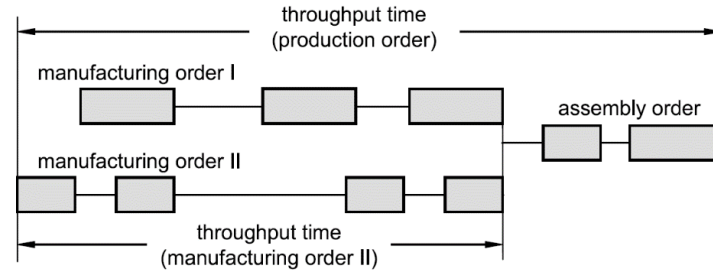
Throughput time (also often referred to as lead time) is a time needed for an order to be completed. From the moment, it was released to production until its completion (manufacturing). Usually on the shop floor level, the throughput time is divided into smaller parts, the throughput times for separate workstations.

As you can see on Figure 7, the process of production of one product can consist of few sub-orders. In this example it is manufacturing order I and II, and after these two are complete, it is an assembly order. All together time needed for these production steps together, is a throughput time.

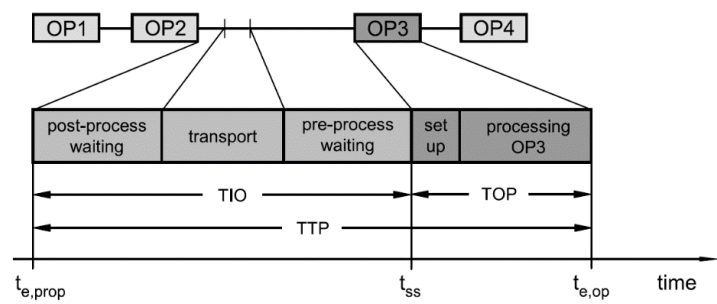
In batch production, the order consists of a production of a batch, for example of 10 products. That means that after they leave one stage of production and come to assembly, there are 10 parts waiting for further processing. It is work-in-process or WIP. Moreover, in batch production the throughput time is lengthened by the wait of production of a batch for each workstation. As the batch moves from one bench to another in a group, so the time that will take one product to be completed is multiplied by the amount of the products in a batch.

The importance of WIP management became especially clear in recent years, with the shift of the production towards such operating model as just-in-time.

On the bottom of the Figure 7, there is separately shown the inter-operation time, it is a time in a throughput period that each production company tries to decrease. During TIO (inter-operation time), the parts are just staying on shop floor as WIP, creating additional costs and no profit.



a) Schedule of a Production Order



b) Operation Related Throughput Element

- $t_{e,prop}$: end of previous operation
- t_{ss} : start of setup
- $t_{e,op}$: end of operation
- $TTP = t_{e,op} - t_{e,prop}$: throughput time
- $TIO = t_{ss} - t_{e,prop}$: inter-operation time
- $TOP = t_{e,op} - t_{ss}$: operation time

Figure 7. Throughput time components and throughput element [8, p 22]

The throughput time length has big impact on delivery time and delivery reliability, especially with just-in-time operation model. For such companies from throughput time depends the length of delivery time and from throughput time reliability and exactness comes the delivery reliability. The shorter the throughput time is the more flexible is the production.

1.2.2 Due date reliability and deviation

Due date deviation means the difference between the planned or targeted throughput time (production time) and actual throughput time (see Figure 8). It can be later or earlier than planned. The lateness for production can be different. Input lateness means that the production order or raw material came in late.

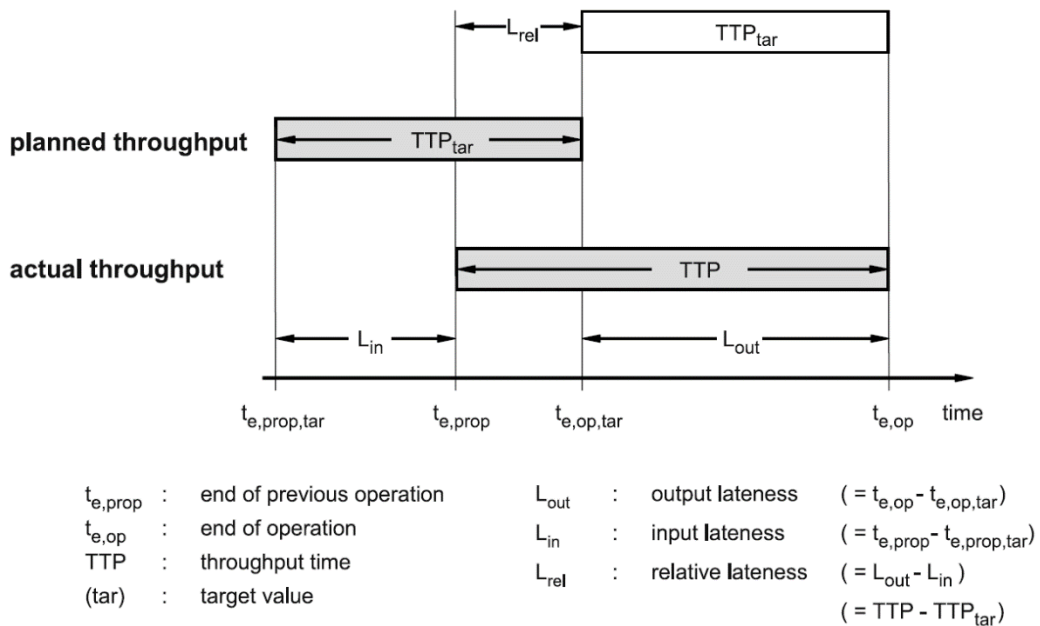


Figure 8. Different types of lateness [8, p 24]

Relative lateness shows the interruption of work during the production. The reason for that could be that the operation for the previous order took longer than planned, and the next one stayed as WIP on the work floor, or the reason could be as simple as machine failure or human shortage due to some reasons.

The output lateness shows how late was the product compared to targeted output time. It is useful for company to gather this data for analysis. The data can be statistically analysed and from that, the due date reliability calculated. It is formulated as a percentage of production output on time during some time period.

The due date reliability can be a remarkable strong advantage over the competition. If the company delivery date is very reliable, then the trust of a customer will be acquired. It can be even more important than the advantage of lower price.

1.2.3 Logistic cost and waste

The purchase price of a product, be it a pen or a car consists of many parts. On Figure 9 is show the rogue sketch of what from consists the price of a purchase. On the surface is the price and this price depends on other company processes.

In recent decades to the monetary value have also added so named customer value. Simple example is when a company chooses between two suppliers, they have similar prices and products quality, but one company provides additional service.

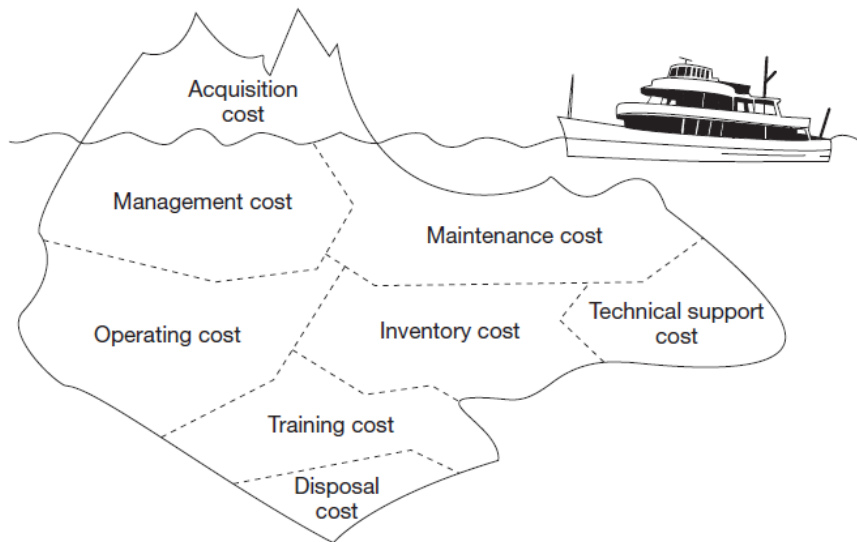


Figure 9. The cost of ownership [10, p 29]

The service is also part of the costs, but usually a small part.

Inventory can be one of the most expensive assets of a company. On Figure 10 is shown the inventory ration to total revenue and assets for some globally manufacturing and service firms. In this list, first two positions are service companies.

At first, it seems that it is easy to manage inventory for service companies, but for example restaurants inventory is perishable and is usually restocked every day. It is a big challenge for operation managers and a nightmare in case that the supplier is unreliable.

COMPANY	FINANCIAL YEAR END	TOTAL REVENUE (\$)	TOTAL ASSETS (\$)	YEAR END INVENTORY (\$)	INVENTORY/ TOTAL REVENUE (%)	INVENTORY/ TOTAL ASSETS (%)
Las Vegas Sands Corp.	Dec 31, 09	4,563	20,572	27	0.59	0.13
MGM Mirage	Dec 31, 09	5,979	22,518	102	1.71	0.45
Microsoft Corp.	Jun 30, 09	58,437	77,888	717	1.23	0.92
Ford Motor Co.	Dec 31, 09	111,308	194,850	5,450	4.90	2.80
Toyota Motor Corp.	Mar 31, 09	208,995	295,857	14,857	7.11	5.02
Honda Motor Co.	Mar 31, 09	103,116	121,735	12,813	12.43	10.53
Wal-Mart Stores, Inc.	Jan 31, 10	408,214	170,706	33,160	8.12	19.43
Target Corp.	Feb 3, 09	65,357	44,533	7,179	10.98	16.12
Pfizer, Inc.	Dec 31, 09	50,009	212,949	12,403	24.80	5.82
Intel Corp.	Dec 26, 09	35,127	53,095	2,935	8.36	5.53
Advanced Micro Devices, Inc.	Dec 26, 09	5,403	9,078	567	10.49	6.25
<i>Note:</i> All numbers in millions, except ratios Source: Annual Reports on Form 10-K						

Figure 10. Inventory to total revenue and assets ratio [9, p 209]

The need for good and efficient inventory management is an ongoing challenge for all companies all over the world. Stagnant stock and poorly managed purchasing strategy shows problems in inventory management and creates unnecessary costs that could be otherwise avoided. Inventory is always a tied up capital that could have been otherwise invested.

Inventory can be divided as a stock in a warehouse and WIP (work-in-progress) in production. Usually WIP is measured in working hours or in number of orders. When WIP increases, the throughput time and utilization rate increases, which is a waste.

As the managers all around the world pay attention to logistic costs, now it is became a trend to also pay attention to logistic (or production) waste. Concept of waste came from lean manufacturing philosophy, which was developed in Japan inside Toyota car manufacture company. The founder of the lean thinking and reducing wastes is: “Taiichi Ohno (1912-1990), the Toyota executive who was the most ferocious foe of waste human history has produced” [11, p 15].

He has developed the principles of lean production in Toyota, and after that from Japan the lean thinking has spread all around the world.

One of the main focuses of lean is waste management. Different authors name the wastes differently, or more precisely describe the same processes with different word. But still all agree, that according to lean, there are 7 wastes, such as: “Transportation, Inventory, Motion, Waiting, Overproduction, Overprocessing, Defects” [12, p 28].

The problem with waste management or elimination is that in practice for companies it is very difficult to see what is a logistic waste. The simple explanation of this is that: “more than 80 percent of the work of logistics takes place outside the view of supervision” [13, p 33].

The transportation waste is a waste of material flow (or information, or documents) in production, such as process input, WIP and output. The most common reason for such waste occurrence is layout that interrupts the material flow.

Motion waste management and elimination can be tricky. It is a waste of unnecessary movement of people (or material) through the company or factory. Many companies don't track this waste, because it seems so insignificant compared to other problems. Still it can make work of an employee easies. After dealing with wasted movement of people,

company can go deeper into operations motion and study the movements of operator on the working place.

Waiting is one of the most important wastes that company needs to reduce, because it affects the customer directly. All the delays that are happening often due to poor planning or bad process structure are delaying the order completion and can cause the loss of a customer. To reduce it, it is important to control and reduce work-in-process. Because the stagnant WIP means, that somebody in a company waits until its completion.

Overproductivity waste usually occur when the company wants to use the stagnant raw material. However, it is often counterproductive, because the personnel was used, machinery and space. This waste is also difficult to find, because during this activity all seem busy, but they are doing work that is not needed at that time.

Overprocessing waste is a process of adding more value to the product than the customer wants (and is willing to pay). Another side of overprocessing is defects, they are not only a waste of resources that were used to produce it, also the process of repairing and reworking produces costs and interrupt the smooth flow of production.

Inventory waste can be easily recognized in a form of gathered raw material (or WIP) in a factory, or a warehouse full of finished goods that are not moving. The sign of big unnecessary inventory can mean three things: one, the production process is poorly planned; two, the layout is poorly planned and for the workers it is difficult to move the WIP on time; and three, the forecast and customer management is bad and a lot of unnecessary raw material was bought because of false information.

The reason for companies to focus their attention on inventory management is simple, in the inventory is tied up a lot of capital. Also, inventory, that is not being used create additional costs (see Figure 11) that could have been otherwise avoided and don't give any profit.

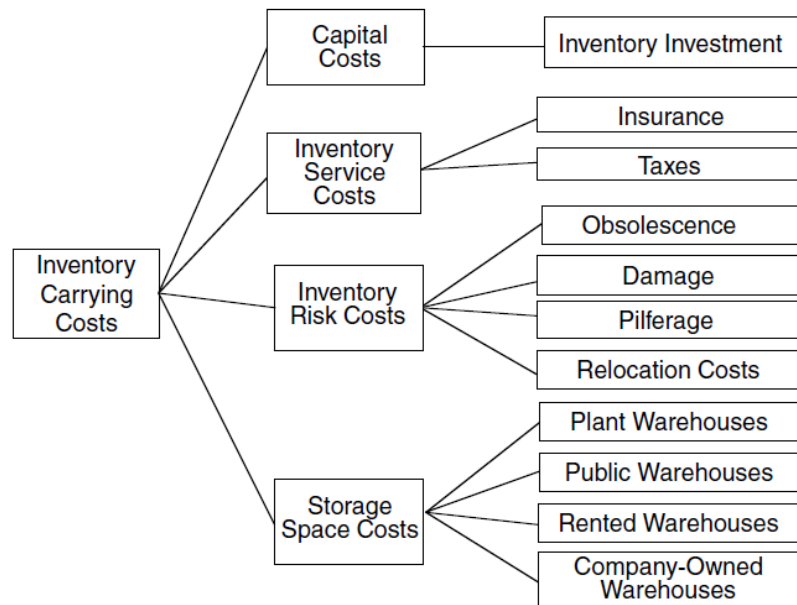


Figure 11. Inventory costs [14, p 43]

1.3 The relation between logistic objectives and their dilemmas

Usually when discussing the logistic objective, authors are not touching the external logistic objectives and the relation between them. German author Lödding explain it with following reasoning: “Due to the variety of factors which influence pricing, it is almost impossible to represent the correlations for the external logistic costs in a comparative form” [7, p 78]. Because of this, the researchers usually focus more on internal logistic objectives relation to each other.

The correct and effective balance between the logistic objectives helps to decrease the production and inventory costs and plan the production. Successful company today is quick to respond to changes in the market by changing the logistic objectives relations. Changing the logistic objectives will affect the cost, price, production capacity and other parameters.

But all authors agree, that the future logistic development should focus on: “loss minimization; efficient use of energy resources; efficient use of material resources and raw materials; efficient use of existing facilities; minimization of environmental impacts; development and implementation of innovative management practices and organization of production processes” [15, p 5].

As it is seen on Figure 12, internal logistic costs roughly consist of WIP levels and utilization level. High utilization level means more machines or people and this produces

additional costs. Low WIP level decreases the cost of inventory, but the higher is the utilization, the higher must be the WIP level to utilize all the capacity of the machinery.

Logistic performance could be measured based on short throughput times and high schedule reliability (see Figure 12). Together combined, this shows the company's performance and this sees the customer. Is the order on time (high schedule reliability), or is the time after ordering and before the goods arrive is short (short throughput time)? Always the customer considers these questions, besides the price and quality of the product.

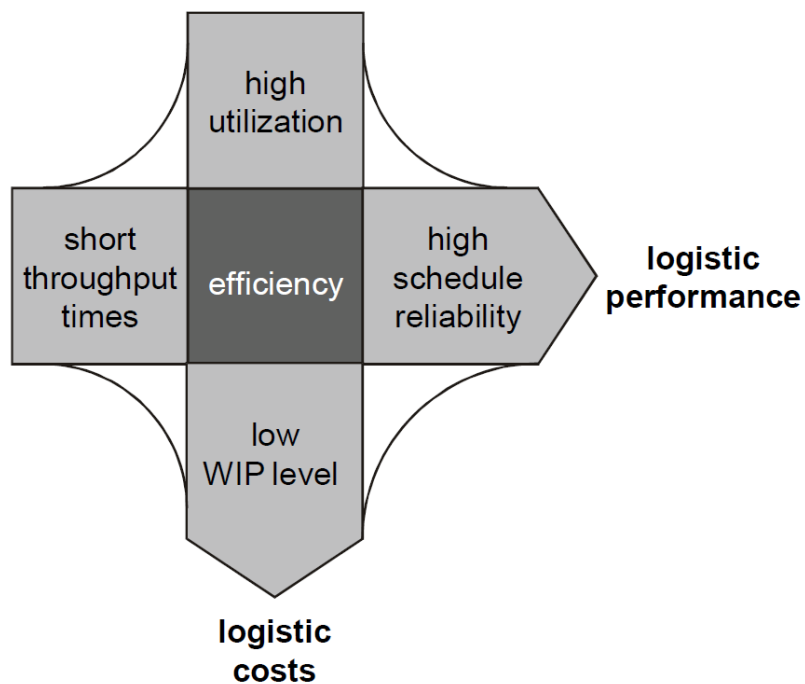


Figure 12. Logistic objectives relation [3, p 371]

However, it is not possible to optimize the logistic objectives simultaneously, because of their co-dependent relation to each other (see Figure 13).

The main problem from production's point of view was already discussed since 1950's. Example could be, Gutenberg since 1950's (German author) and the problem is known as *dilemma of operation planning* [7, p 34]. Closely related problem from the field of operations planning is *scheduling dilemma* [3, p 372], by the same author Gutenberg in year 1951. The scheduling dilemma deals with relationship of all four objectives (see Figure 13).

It is not possible to have maximal utilization rate and lower throughput time, because to have lower throughput time, the production must use lower levels of WIP (so that there

was no queue near the workstations), but if production uses low levels of WIP, the utilization rate will decrease.

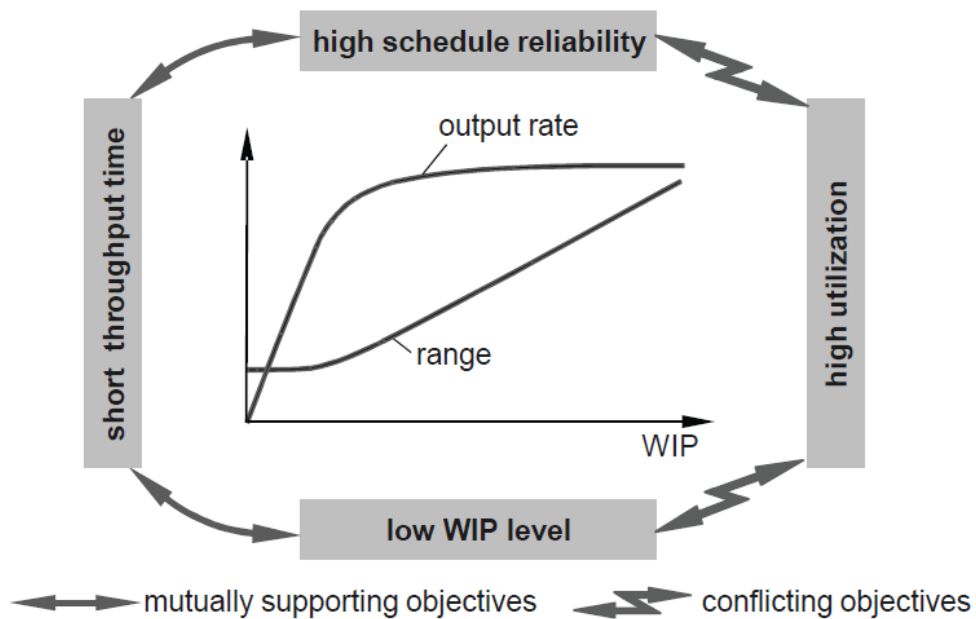


Figure 13. Scheduling dilemma [3, p 372]

It is the main dilemma of production, it is not possible to create one universal solution for solving it. Each situation, each company's production process should be analysed and first it should be decided what is more important for them, to use full capacity of one expensive working bench, or it is more useful to decrease the WIP levels and free the capital, used for internal inventory.

Nevertheless, it is important to remember, that all processes in a company are interlinked. Therefore, when changing something, it will affect other processes. Similar to logistic objective the Japanese lean philosophy has similar concept. The company processes as a whole are forming a complete system, in lean manufacturing this system was first named as *Toyota production system* [14, p 235].

Figure 14 shows the dependencies of processes in production according to Toyota production system. Changing one parameter, will lead to other changes.

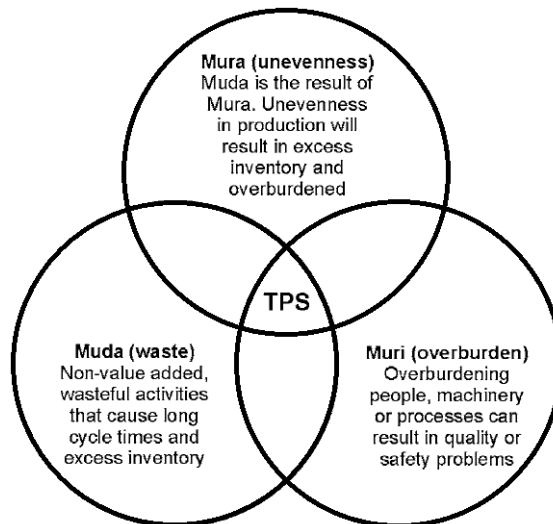


Figure 14. Interrelation of processes in production according to Toyota production system [14, p 236]

Which strategy to choose? How to plan the production? First step, is to analyse the current situation in production, decide on the changes, and then to simulate these changes. For that various techniques and tools are used. In this paper will be used one them.

1.4 Conclusion

For today's companies the main objective is to answer the customer's demands, be the customer the end-used or a producer. To do so it is important to shorten the delivery time and delivery reliability, manage correctly the company's service level and be aware what is happening inside and outside the company.

The company today is a complicated network of interrelated processes (see Figure 15). To have a market success, it is important to improves them all and not focus only on one area.

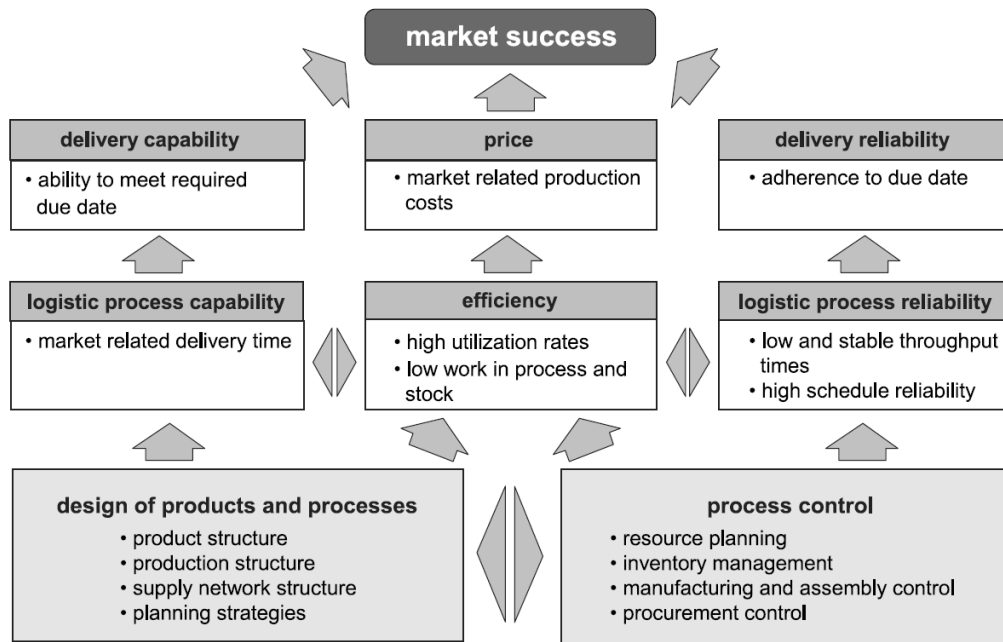


Figure 15. Logistic key performance indicators [8, p 21]

Today the market is extremely dynamic and it can change rapidly, because of that it becomes increasingly important to manage the inventory, be it external or internal, raw materials, sub assemblies or finished products. What import is: “to maintain a certain service level with respect to the subsequent buyer, whether this is a producer or consumer” [16, p 1] and “to ensure an appropriate service level while at the same time taking into account economic aspects” [16, p 1].

The inventory management can not only save money and reduce costs; it is also an important instrument in process improvement. Excess WIP can interrupt the workflow, especially near the bottleneck processes. On one hand, big WIP amount can show the location of a bottleneck in a process, on the other hand, big amounts of WIP make the work of such station less efficient and increases unnecessarily the throughput or lead time of a production.

The dilemma that occurs while balancing on one hand the desired higher service level and on the other hand the wish to minimize inventory levels is called: *dilemma of inventory management* [8, p 223].

The first step is for a company to describe for themselves how these different objective are related to each other. After finding the common points, it is possible to plan and change them depending on the market demand.

The dilemma of inventory is connected with the scheduling dilemma, only the first one is dealing with the whole company, the second is located in the factory or if narrowed more, on the level of one working station.

The success of a company starts from smooth operation on one work station.

2. Modelling techniques

Optimization is a very broad used term today. It refers to a process of selecting the best possible factors and strengthening them and eliminating the worst. For that are used various techniques to analyse the existing production or other business process, then making adjustments and simulating the optimized process again. After that, the changes are implemented into the company.

However, before making decisions for changes, first, the existing situation must be measured and problem areas found. After that, the decision is made, but it is not advised to immediately implement it, the new decision should be analysed and the changed process in a company should be calculated and measured with new data. If the result is satisfactory, it can be implemented in reality. As the production became more complex and the amount of data and processes became too much to handle for one person, to make decisions and to optimize the companies processes, various modelling techniques were created.

Authors from different countries propose and describe different techniques for process analysing and modelling, but the general classification of modelling techniques is almost always the same. For example, authors from America and Britain propose following classification of processes modelling: “mathematical techniques, heuristics techniques, simulation, and genetic algorithms” [18, p 380].

Another example is from Russian author M. A. Korablin: “mathematical programming, simulation programming and genetic algorithms” [19, p 6].

As a conclusion we can use the following classification of modelling techniques:

1. Mathematical modelling,
2. Simulation modelling,
3. Genetic algorithm,
4. Heuristic techniques.

The most commonly used are mathematic models. This method uses mathematical equations to measure the processes that are being evaluated. The most commonly used techniques are: linear and nonlinear programming, MIP or Lagrangian Relaxation. All those are fully developed, were used and tested many times. It is a reliable method to analyse and to help to make a decision while optimizing some processes in a company.

The weakness of mathematical solutions is that the problem may be too complex and as the result, the mathematical model becomes too big and complicated. In that case, the problem is usually simplified, but due of this, the result could be too far from reality.

Second method is simulation, where the software (for example Arena, AutoMod, SIMFLEX and others) is used to describe the existing situation in reality. Then it can model the changes that could be done to the system, or the program can even propose the solution to existing problem, optimize the model of existing production.

Today in companies it is becoming a very popular tool to use. However it has a few drawbacks. It is very expensive and to make a simulation a lot of efforts and 'clean' data (or the result will be far from reality) are needed. After creating the model, the time is needed to analyse the report that the program provided. Another weakness is that even after all that it is not guaranteed, that the model will provide the company with optimal solution. Or that the solution could be implemented in real life due to some reasons.

Third model is genetic algorithms. It is a part of evolutionary algorithms, which were created by using the nature's processes, such as genetic selection, mutations, crossover and so on.

With this model it is possible to search through big quantities of data, where said data is complicated and unpredictable. As it uses the nature's process, it enables the best data to survive the evolution and the worst to die out. As the result, a few optimal solutions are presented.

Big weakness of these solutions that from the data different chromosomes must be created and then the mating process defined. After that the constrains must be designed and implement inside the model, which is not an easy task, therefore this method could not be used for all companies processes optimizations and requires a lot of data preparation, handling and re-classification.

The last solution, that some authors do not consider as a modelling technique, but still it is often used while making decisions, is heuristic technique. Basically this technique uses the intuition of an experienced person, the gut feeling. Said person uses his or her common sense, intuition and gathered experience to make a decision. It is not guaranteed, that this decision will be optimal. Still, this technique could be used on the non-essential stages of a project to save time. In addition, it is very frequently used in small or medium enterprises,

where the amount of workers and processes is small and the planning is manageable for one person.

As the simulation software is usually very expensive and to use it, special skills and training is needed, for small and medium companies it is more useful to use mathematical modelling (also mathematical modelling can be used in bigger enterprises for planning of one production line work or a workstation).

However, independent of the method, during the solving of a problem, the model undergoes gradual changes and modifications (see Figure 16), till it is adjusted perfectly for the purpose it was created for. Still, the model will be as good, as the data based on which it was created and even the perfectly adequate model will not guarantee the solution to the problem.

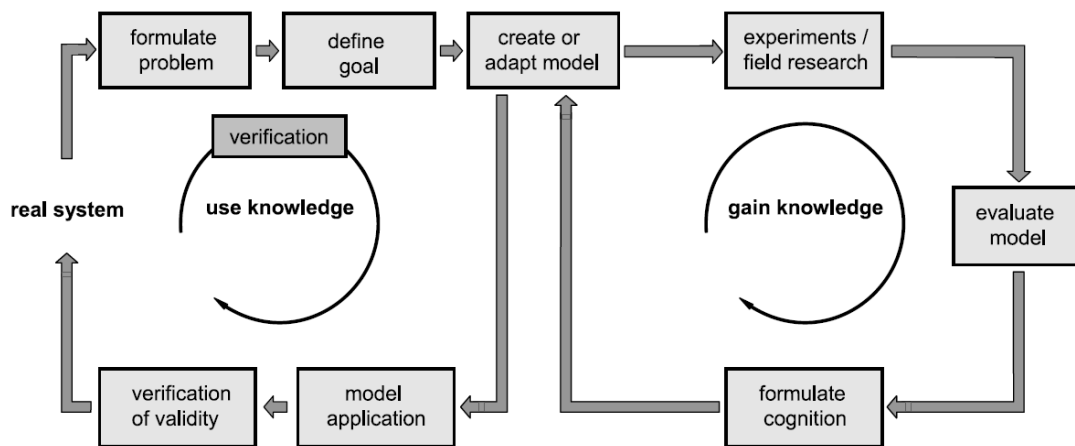


Figure 16. Model based problem solving cycle [8, p 25]

After all was done, the next phase starts, the implementing of found solution. It is the most critical step of the project.

To model the behaviour of logistic objectives in a company (for example for creating the optimal schedule), the most popular models are: “the queuing theory from the field of operations research, simulation and the Theory of Logistic Operating Curves” [3, p 373]. But the effort needed for implementing a model is different for different techniques (see Figure 17).

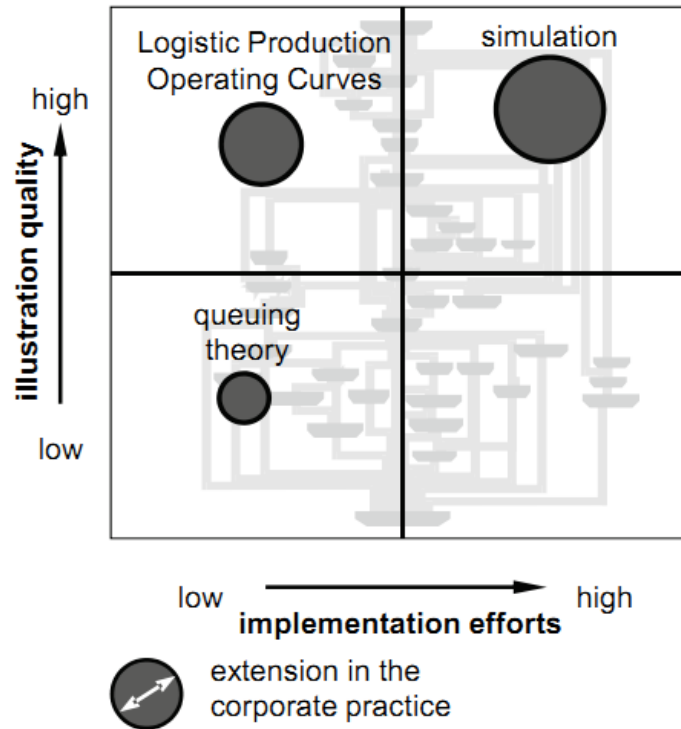


Figure 17. Quality and implementation efforts relation for modelling techniques [3, p 373]

As a result, the mathematical models are the preferred method of analysing the production for small and medium companies. In big enterprises, the simulation is used, but usually for big projects and big changes. To analyse and predict the behaviour of smaller parts of production (workbench or line), usually the mathematical techniques are used.

For example, one person did a spreadsheet in Excel, with formulas, and another just inserts the data into correct cell.

Unlike the simulation programs, this way, any worker can use the mathematical model after short explanation. However, to correctly create a simulation program, special knowledge and training is needed, which additional to the price of a software, increases the cost more.

2.1 Queuing models

For creating and analysing the schedule mathematically, one of the possibilities is the queuing model. The queuing model was first used for calculating the telephone calls queues and after that it became widely spread as a tool for WIP and waiting time calculating, that can be influenced by the input to output ratio.

The studies were made and it was estimated, that there are approximately twenty-five queuing models, which could be divided into three classes.

The biggest weakness of a queuing model is that, even if it is widely discussed and used in theory, it is not often used in practice. This happens because with queuing modelling the input and output processes should be first researched and the conditions for preconditions of deviation must be proved.

In practice, the model or method applied for everyday usage should be simpler in terms of data entry and gathering.

Second weakness of queuing model could be that even if with the more modern queuing models the data entry is simplified, the accuracy have decreased, because such models are done based on estimations. Because of that, the result is not precise.

Third weakness is that for applying the queuing theory, special knowledge is needed. First, it should be chosen what type of model should be used, second the data needed for it should chosen and appropriately processed and then the modelling starts.

Even after all that the main problem remains: “To some extent it is generally questioned how realistic queuing models are” [8, p 47].

This insecurity comes from the reason that, often mistakes are made when creating the queuing model, especially if there is faulty data or more precise the incorrect estimation of the distribution parameters. Without knowing the right distribution of income and outcome processes, the modelling of a feasible queuing model is impossible.

However, in practice it is very difficult to do, even with the existing of real production and real workstations, and even after estimating the correct data, the dynamic of the production processes can greatly change over time, and after some time correctly working model becomes incorrect.

The difficulty in creating the model due to complicated input data analysis and the estimated and approximated results are the main reasons why the queuing theory is not used more often in real production companies.

2.2 Simulation

Before discussing the advantages and disadvantages of simulation, it is needed to define, what is simulation, because: “tool in the simulation process may range from spreadsheet or even simple calculator..., to the whole power of the simulation science in Artificial Life or in Virtual Reality” [4].

However, in this paper under term of simulation is understood the computer software that enables the user to input data from real production and simulate it. Today simulation is very widely spread tool for analysing the complex systems.

The simulation is good in cases, when other analytical methods could not be applied and it is not possible to test the changes in real production.

Today there are many different simulation software. Example of most popular are: Enterprise Dynamic, Arena, AutoMod and SIMFLEX.

Various software is better suitable for different purposes. For example, SIMFLEX is usually used to design and analyse supply chains; AutoMod has big possibilities for 3D modelling and so on.

What all these software have in common is that it needs serious training before using it. Few hours of training will allow to use the main functions and features of the software, but to better understand features that are more complex and to model more complicated systems, the training should be deeper. Also reading the manual could help. However, usually the manual for this type of software consists of hundreds of pages and still, it not always helps.

While for the professional to create a model from existing data is usually a matter of few hours (depending on the size of a system), for persons not used to using the software, it is the work of a few days or with big and complex systems, even weeks or months.

Still even after all that, it could so happen, that some manufacturing processes could not be simulated with a software due to the limit of the processes that are possible to simulate, or other reasons.

Another problem of using simulation is that sometimes the data that is needed to complete the simulation cannot be so easily acquired due to cost or time, or simply because it is difficult to measure.

To test the changed capacity or process flow is also could be difficult, because the model structure and parameters also should be changed. All changes to big, complex models can lead to mistakes when the user simply forgets to remove some number somewhere. So even if the simulation allows the modelling of big and complex systems, the bigger is the system and the more there are connections and elements, the higher is the possibility is that

the model creator have done some minor mistake, that will be not noticeable while running the model, but still will influence the result.

Sometimes the simpler it is – the better it is.

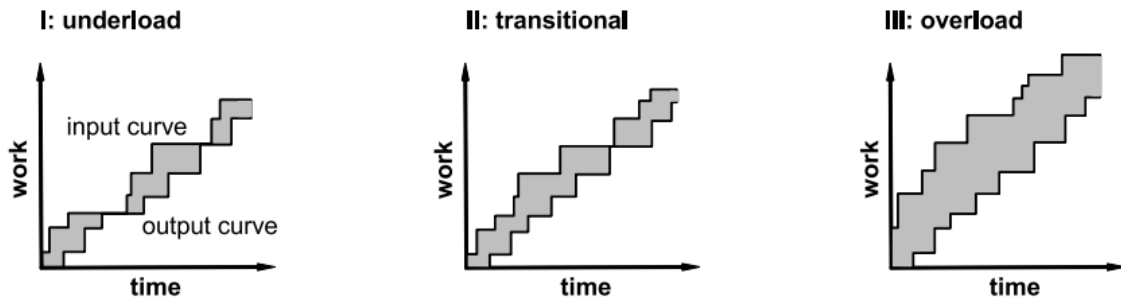
Lastly, the biggest issue with the simulation software is the price. There are some simulations that are cheaper; there are those that cost tens of thousands. There are cases, when even some big companies are not ready to spend money on a tool that will not guarantee results. For small or medium enterprises, the price of the software is often simply not affordable.

Still, since the first computer simulations have emerged in the beginning of 80's, the simulation software have greatly developed: “Since that time, simulation-modelling products have advanced significantly due to both computer hardware and software developments” [19, p 68]. They became more flexible and user friendly. Still, for many small and medium companies to use the simulation software for production planning will be like killing ants with a bomb. It will be an investment that most probably will not be returned, because the complexity and all abilities of the software will not be used.

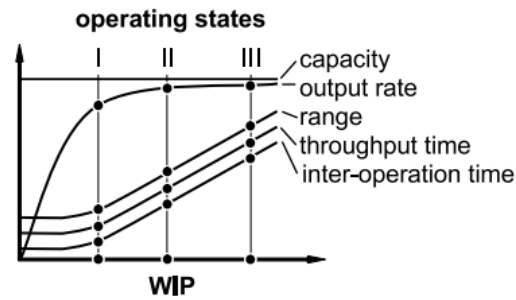
2.3 Logistic operating curves

Logistic operating curves dynamically show the production situation on a workstation. But still, only the logistic operating curve is usually not enough to describe the production system, so usually other diagrams are included in the analysis.

On Figure 18 is shown how the logistic operating curve looks (section b) and also the throughput diagram, which is used for seeing the loading state of a station (section a).



a) Typical Operating States



b) Logistic Operating Curves

Figure 18. Different production states based on the logistic operating curves and the throughput diagram [8, p36]

First operating state shows how the diagrams will look like in an underloaded situation. On throughput diagram is seen, that the input and output curves some days have even collided, which means, that there is no work on the working station. State I on the logistic operating curve is shown as a vertical line, it shows the present state of a workstation. It could be seen, that the output rate curve is far below the capacity of a workstation.

In state II is shown the optimal working of a workstation. On throughput diagram it is shown when the input and output curves behave parallel to each other and the area between them is not wide. Of course usually the situation in production fluctuates due to various reasons, so the relation between the curves is not perfectly constant. But from the logistic operating curves for situation II we still see, that the output of the system is optimal. The point is precisely in an instant, when the output is at it's peak, but not far from the 'fall' zone.

If the point is moved further right (state III), it will be already the overload. The production was feed with order that could not be put into processing right away, so they are most probably waiting in a queue, and tying the internal inventory, WIP. In throughput diagram overload is seen as a wide area between the input and output curves.

As it is seen from the example, the logistic operating curve is highly visual model. It's calculating is based on the basic laws and equations of the operations planning.

The input data needed for the modelling is the basic that is known in production: the day the order was released in production, the day it should be produced (or is produced, if the model is based on past data), and the work content of said order. Also the data regarding the workstation: capacity. And lastly, the WIP that was left in a system from previous production period (if there is any).

Based on the data acquired after calculating the logistic operating curves, the adjustments to scheduling could be made.

2.4 Conclusion, choosing the model

For a company to be successful, it needs to be flexible and be able to change quickly according to the demand. If it's a company with volatile demand, the production control and planning is even more important.

There are a lot of different models for planning and controlling. What they all have in common that the production system is simplified to some degree (with some models it's bigger, with some less) to help and manage it easier.

However, even for small production entities, such as assembly station or machining station the logistic objectives behaviour still stand. High utilization requires high WIP, but high WIP creates additional costs and longer throughput times.

The companies manage it by deciding what is the most important objective for them to manage. With time, the objective's importance can shift to other aspects and the whole production planning should be done differently, focusing on another objective.

Nevertheless, even knowing what objective is important for the company, to manage them is another problem. First, it is needed to correctly describe the relationship between the logistic objectives and for that appropriate model or tool is needed.

The model should show the production system, maybe abstractly, but the described parameters should concentrate on relevant objectives. From the model it is not required that it simulates the production with precise exactness, it needs to show the important objectives with sufficient similarity to real numbers, so that from the result could be drawn a conclusion.

On Figure 19 the tree models, used to model the production are compared. There are advantages and disadvantages, and each company should decide for themselves to what criteria's pay more attention.

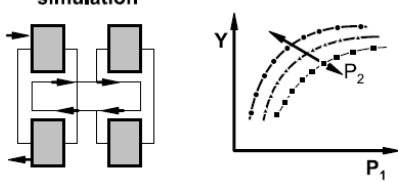
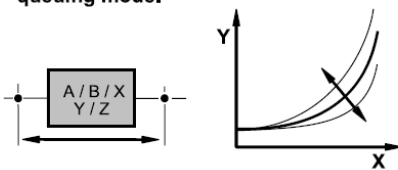
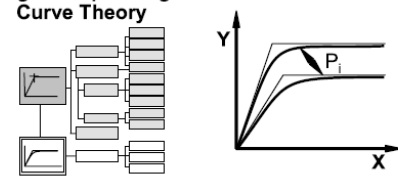
modeling approach	disadvantages	advantages
<p>simulation</p> 	<ul style="list-style-type: none"> • model validity can only be proven in points • necessary to re-build model for every application • results cannot be generally transferred • greater application effort 	<ul style="list-style-type: none"> • minimal development effort • possible to adapt model • can describe single events • highly accepted
<p>queuing model</p> 	<ul style="list-style-type: none"> • great development effort (non-recurrent) • model can only be limitedly adapted, if at all • parameters to some extent do not meet practical conditions • limited to resources perspective 	<ul style="list-style-type: none"> • model structure and parameters are derived from basic laws • minimal application effort
<p>Logistic Operating Curve Theory</p> 	<ul style="list-style-type: none"> • greater development effort (but non-recurrent) • limited to resources perspective 	<ul style="list-style-type: none"> • model structure and parameters are mostly derived from basic laws • minimal application effort • model can be adapted within defined limits

Figure 19. Comparing different approaches used for production processes modelling and scheduling [8, p 284]

To compare and choose the model for solving the problem of scheduling for a small or medium enterprises company, table 1 was created.

In the first column are the weighted criteria's, they were chosen based on the most important aspects for the small or medium enterprises production planning. The result visibility, development and implementation effort, input data needed, is it easy to use it, which model is more suitable to resolve the problem and one of the most important criteria is the cost of the model.

The score was placed for each cell, corresponding to the model used for production processes modelling. If it's 1, then the criteria is badly suited to the small or medium enterprise problem solving, 2 is medium and 3 is the best suited to the company.

The bigger is the total score, the better it is. Based on this evaluation it is seen, that the logistic operating curves model is the most suitable to solve the problem of a small and medium enterprises production scheduling.

Table 1. The comparison of models suitable for creating a schedule for production

Important criteria (1-bad, 2-medium, 3-good)	Simulation model	Queuing model	Logistic operating curves
The production system behavior is clearly seen	3	1	3
Development efforts and knowledge needed	1	2	2
Implementation efforts	1	3	3
Amount of data needed	1	3	3
Easy to use	1	1	3
Suitability to the problem	2	1	3
Cost	1	3	3
Total score	10	15	<u>20</u>

While comparing literature it could be seen, that the logistic operating curves method is not very well known modelling method outside of Germany. Still, it's universal (logistic operating curves methods could be used for analysing one working station and also the whole factory as a whole) and unlike with simulation software, it can also be used by a person, not related to the creation of said simulation.

However, as with usage of any tools, there is a danger of receiving faulty data. As the best simulation software in the world cannot create simulation similar to reality, if the inputted data (or processes algorithm) is wrong.

So it is important to remember, that any the model is only a useful tool. Example of such mistakes in modelling could be a simulation with constrains that have changed. Like the demand for a month or utilization rate. Utilization rate could be changed by hiring more people or adding a shift. The usefulness of a model depends on: "The appropriate formulation of a model depends on the decision it is intended to assist" [20, p 229].

It is also important to consider the frequency of use. If the model is regularly used for production planning, the personnel is used to it and can adequately interpret the results and

use it correctly for adjustment of production processes. Additionally the effort of using the model will be lower with each application of the model.

For the purpose of production planning of a small company, EXTREME-MET, because of above explained reasons; such tool as logistic operating curves was used.

3. Calculating a throughput diagram and other parameters

The logistic operating curves visually shows the relation of dependent logistic objectives and also the independent variable, which can be influenced.

Usually the independent objectives, which could be influenced from outside are WIP, throughput time and output rate. Dependent objectives is always the logistic production cost and schedule certainty. These factors cannot be changed so easily, they can only be influenced through other objectives.

On Figure 20 is shown the logistic operating curves according to WIP levels. The throughput time rises with the level of WIP, but the throughput curve cannot fall below some minimum due to the specific operation technology. Short throughput times are more predictable, and from that increases the schedule adherence, as shown on Figure 20.

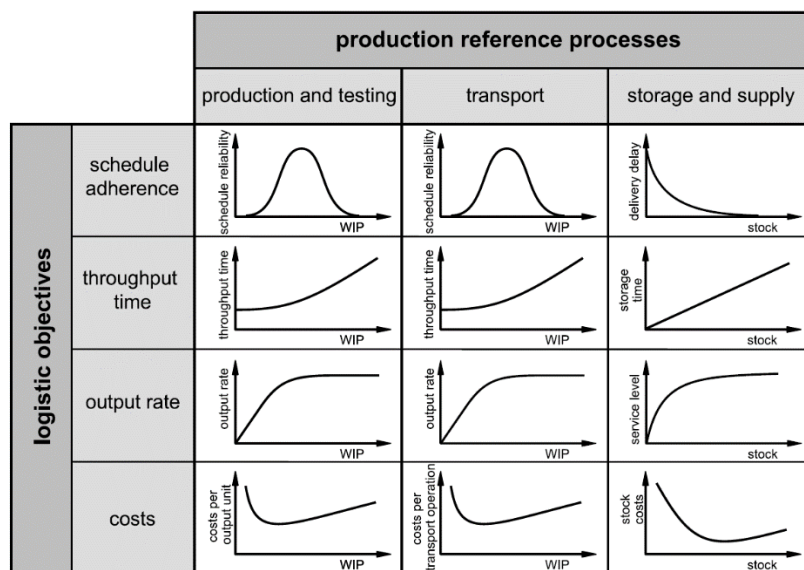


Figure 20. Logistic operating curve types [8, p 12]

The output rate depends on the level of WIP up to a certain level (capacity maximum), but if the WIP level falls, the output rate decreases due to raw material shortage. Then there is cost operating curve. It clearly shows the cost depending on WIP level. Below certain WIP level, the cost rises due to machinery idle time, but when WIP levels rises above the line, cost increase due to bigger stock cost.

With the help of the logistic operating curve it is possible to simulate the point, where all objectives are in balance and are not producing additional costs to a company. Of course, in real life it is almost impossible to operate under perfect conditions. Vendor lead times

can vary and safety stock is needed, some machinery may stay idle because it is used only for some special orders. Still the LOC (logistic operating curves) model will show where the company should aim for.

The logistic operating curves consists of throughput time operating curve and output rate operating curves. These two are calculated with based on the funnel model and throughput diagram.

In chapter 3 are explained the calculations that are needed for building the throughput diagram, in chapter 4 will be explained the calculations of the logistic operating curves.

All formulas are taken from a book “Fundamentals of Production Logistics” [8], by the authors P. Nyhuis and H.P. Wiendahl.

3.1 Calculating work content and operation time

The basic parameter of funnel model is work content (WC). Work content is the time that will be spent for production of an order, be it one ordered piece or pieces. It is calculated:

$$WC = \frac{(LS \cdot t_p \cdot t_s)}{60} \quad (1)$$

where WC – work content (hours),

LS – lot size (units),

t_p – processing time (minute/unit),

t_s – setup time per lot (minutes).

As the work content usually strongly vary, the average is needed to be calculated. For that is used equation:

$$WC_a = \frac{\sum_{i=1}^n WC_i}{n} \quad (2)$$

where WC_a – average work content (hours),

WC_i – work content for individual for an operation (hours),

n – number of operations.

After that is calculated the range of distribution with the help of standard deviation equation, in this case it will be:

$$WC_s = \sqrt{\frac{\sum_{i=1}^n (WC_a - WC_i)^2}{n}} \quad (3)$$

Where WC_s – standard deviation for work content (hours),

WC_a – average work content (hours),

WC_i – work content for individual for an operation (hours).

The variance of the distribution with relation to the average, can be calculated and the coefficient of variables can be found.

$$WC_v = \frac{WC_s}{WC_a} \quad (4)$$

where WC_v – coefficient of variation for average workstation,

WC_s – standard deviation for work content (hours),

WC_a – average work content (hours).

Next step is finding how long the workstation is occupied in shop calendar days (SCD), this parameter is also known as operation time.

$$TOP = \frac{WC}{ROUT_{max}} \quad (5)$$

where TOP – operation time (SCD),

WC – work content (hours),

$ROUT_{max}$ – maximal possible output rate (hrs/SCD).

The maximum output rate is a result of the capacity, so it can be changed, if the capacity is changed by working overtime or adding one more worker.

The coefficient of variation for operation time is equal to coefficient of variation for work content in case that the LOC is used for one working station, where the maximum output rate does not change or is independent from the work content of the individual operations.

$$WC_v = TOP_v \quad (6)$$

where WC_v – coefficient of variation for average workstation,

TOP_v – coefficient of variation for operation time.

3.2 Calculating throughput time

The throughput time is calculated with the following equation:

$$TTP = t_{eop} - t_{epo} \quad (7)$$

where TTP – throughput time (SCD),

t_{eop} – end of operation (SCD),

t_{epo} – end of previous operation (SCD).

The average throughput time is calculated with equation:

$$TTP_a = \frac{\sum_{i=1}^n TTP_i}{n} \quad (8)$$

where TTP_a – average throughput time (SCD),

TTP_i – throughput time for individual order (SCD),

n – number of orders.

But inside the throughput time is also included the interoperation time, which consists from the waiting times, times needed for setup and other interruptions, that are often not recorded in companies. To calculate this time, following equation is used:

$$TIO = TTP - TOP \quad (9)$$

where TIO – interoperation time (SCD),

TTP – throughput time (SCD),

TOP – operation time (SCD).

The average interoperation time could be calculated by the means of average throughput time and operation time:

$$TIO_a = TTP_a - TOP_a \quad (10)$$

From equation 10 we can find the average operation time:

$$TOP_a = TTP_a - TIO_a \quad (11)$$

The flow rate can be calculated as relative measure:

$$RF_a = \frac{TTP_a}{TOP_a} \quad (12)$$

where RF_a – average flow rate,

TTP_a – average throughput time (SCD),

TOP_a – average operation time (SCD).

3.3 Throughput diagram

After finding the throughput times, it is possible to draw in Excel or on a paper the throughput diagram.

Similar to funnel model (see Figure 21) in chemical industry, the production can be described with the throughput diagram. The flow of production can be described through the input, WIP and output.

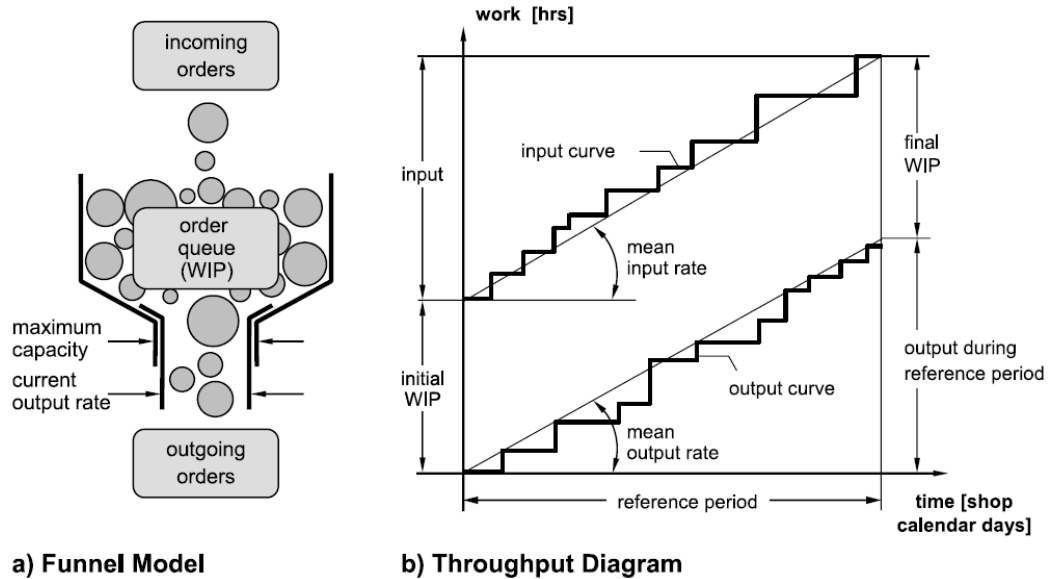


Figure 21. Funnel model and throughput diagram [8, p 25]

The capacity unit (workstation or assembly line, or the factory) are similar to the funnel, where the orders arrive, and independent of the lot size, they are staying in a queue, while other orders are being processed. After the order is complete, it goes out of the funnel. The opening at the end represents the output rate, at the beginning is the input rate.

The funnel behaviour can be also shown in a diagram. In that diagram, the x-axis shows the time flow in shop calendar days (SCD), and the y-axis shows the work content (WC) in working hours. On this diagram is then positioned the input curve, output curve and WIP curve (see Figure 22).

The throughput diagram shows the chronological picture of the production system behaviour. In addition, it allows seeing the impact the logistic objectives have on each other.

3.4 Calculating output rate and utilization

From the throughput diagram could be also calculated the average output rate. The average output rate is calculated from the ration of the duration of researched period and output *OUT* (see Figure 22).

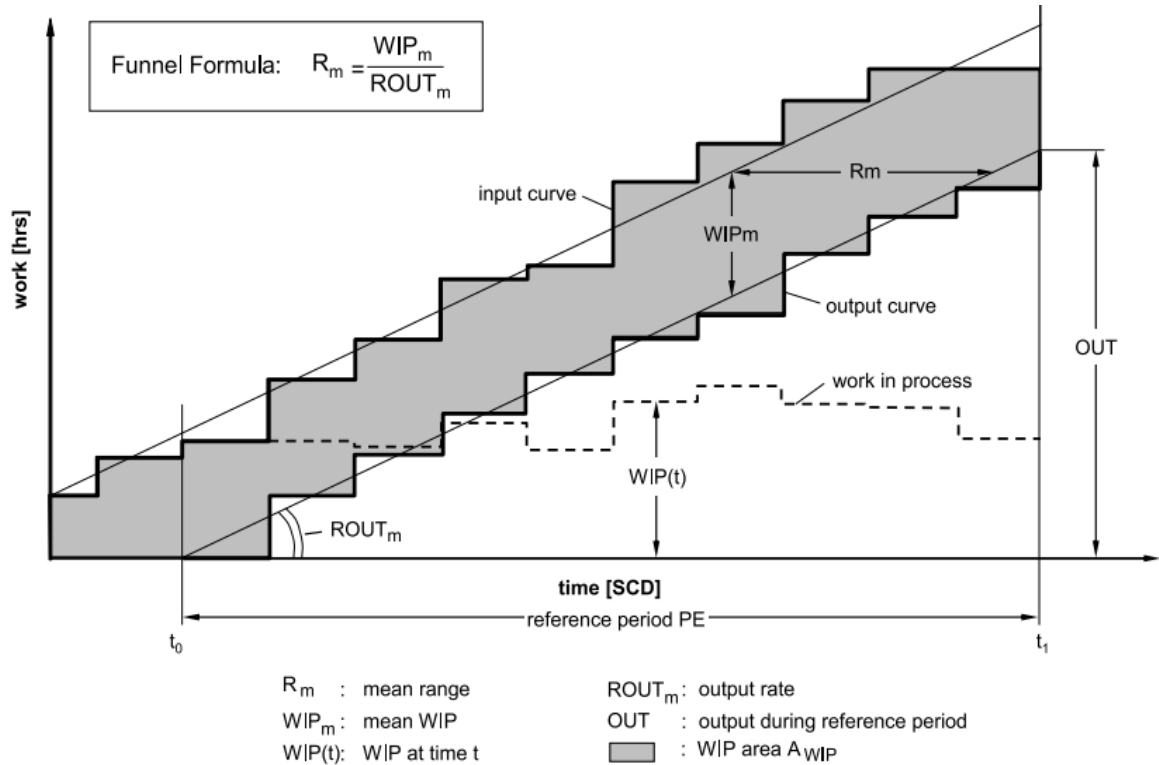


Figure 22. WIP, range and output rate in a throughput diagram (4, p 26)

The average output rate can be found with the following formula:

$$ROUT_a = \frac{\sum_{i=1}^n WC_i}{PE} \quad (13)$$

where $ROUT_a$ – average output rate (hrs/SCD),

WC_i – work content per operation (hrs),

n – number of operations,

PE – researched period (SCD).

The correct way for production to operate is to compose one completion note for operation. If there was made a mistake, and two completion notes were written, it will impact the calculations and make them not so precise as they could have been.

However, research have shown, that the longer is the reference period, the less this kind of mistakes will influence the model and that allows ignoring this kind of data imperfection.

The utilization can be found as the ratio between the average output to possible output:

$$U_a = \frac{ROUT_a}{ROUT_{max}} \cdot 100 \quad (14)$$

where U_a – average utilization (%),

$ROUT_a$ – average output rate (hrs/SCD),

$ROUT_{max}$ – maximum possible output rate (hrs/SCD).

3.5 Calculating work in process

Work in process is shown as the distance between the output and input curves. It also corresponds to the work content of the orders that are waiting and the work content that is being processed. Formula for calculating the work content is simple. It is the sum of the WIP during separate time periods, divided on the number of said time periods:

$$WIP_a = \frac{\sum_{t=t_0}^{t_1} WIP(T)}{z} \quad (15)$$

where WIP_a – average WIP (hrs),

$WIP(T)$ – WIP during time period T (hrs),

z – number of time periods.

The ratio of average WIP to average output rate corresponds to the WIP average range. This formula is also called the funnel formula:

$$R_a = \frac{A_{WIP}}{OUT} = \frac{WIP_a}{ROUT_a} \quad (16)$$

where R_a – average range of WIP (SCD),

A_{WIP} – area of the WIP (hrs·SCD),

OUT – output during researched period (hrs),

WIP_a – average WIP (hrs),

$ROUT_a$ – average output rate (hrs/SCD).

3.6 Calculating weighted throughput time and range

To show the throughput time in throughput diagram, additionally to output and input curves, the throughput elements for each operation is put on the diagram. Based on this information, the conclusion about the workstation's behaviour can be made. In case the

orders are processed on the principle, came first, processed first, the throughput curve points will be placed between the input and output curves.

If the beginning of the throughput curve differ strongly from the input curve, it shows that the sequence was changed. Orders are going through the workstation directly after the input, but the other orders that came during processing are staying in the queue. This mess will lead to the longer throughput time of an order.

On the throughput diagram can be seen, that the throughput element on the horizontal line are formed by the order's input and output dates. On the vertical line they are formed by the order's work content (see Figure 23).

The sum of these is the throughput time area (*ATTP*).

Like in a WIP area calculation, if the throughput area is set in relation to the output, then when the range is calculated, the result will be in creating one more parameter, weighted average throughput time:

$$TTP_{aw} = \frac{\sum_{i=1}^n (TTP_i \cdot WC_i)}{\sum_{i=1}^n WC_i} \quad (17)$$

where TTP_{aw} – weighted average throughput time (SCD),

TTP_i – throughput time of some operation i (SCD),

WC_i – work content of some operation i (hrs).

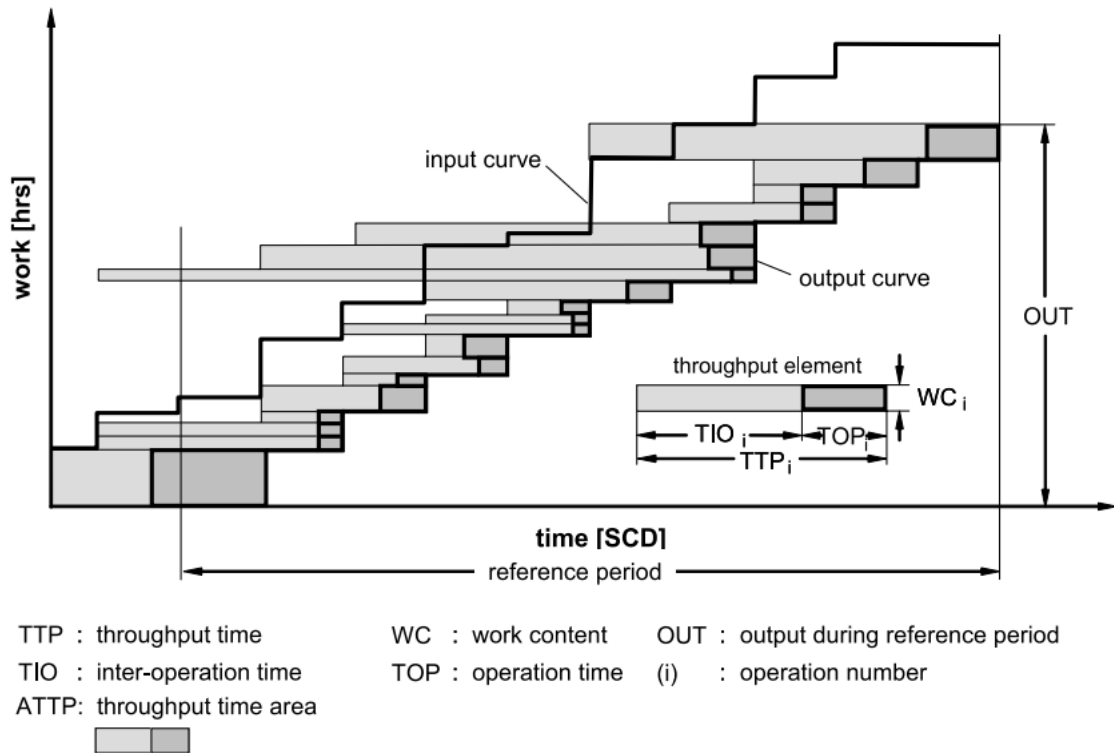


Figure 23. Throughput element in throughput diagram [8, p 29]

The conclusion about behaviour of WIP can be made based on the throughput diagram. If the input and output curves are parallel (ratio between WIP and output rate is the same), then that means that the throughput time area (see Figure 23) and the WIP area (see Figure 22) corresponding to each other.

From this follows the following formula:

$$R_a \cong TTP_{aw} \quad (18)$$

where R_a – average range (SCD),

TTP_{aw} – weighted average throughput time (SCD).

But with shorter reference period this ratio can change. With longer period this ratio is a given.

4. Calculating logistic operating curves

With the throughput diagram and the parameters that were calculated the logistic objectives dependency have been explained not enough. The question about the lowest throughput time, the schedule derivation, the minimum WIP without the loss of output, cannot be answered with throughput diagram alone.

However, the logistic operating curves can help with this. As a function of the WIP, logistic operating curves show the relationship between such parameters as output rate, throughput time and range.

The performance figures and throughput diagram are describing the present state of workstation operations.

The output rate curve shows the rate of WIP on a workstation. That means, that when the workstation is loaded to a certain point, the output rate will not increase further (cannot be higher than the workstation capacity level), even if we add more WIP. Nevertheless, if the WIP levels are not sufficient, the output rate will be lower that it could have been.

The operation points that are shown on the LOC are the present status of workstation with current input data. The areas behind and before this point show what will happen, if the WIP level will be changed. So to drastically change the LOC, the process settings should be changed.

The LOC can be applied to any production system, because the general dependencies are applied to all of them. Lower WIP levels will shorten the throughput time, but it also can lead to material shortage and lower utilization rate.

It is almost not possible in actual production to search for the ideal WIP level. Because the series of tests that will be done there will interrupt the working of a factory and produce additional unnecessary costs.

To see on example, what the LOC can show, is possible in chapter 5.

4.1 Calculating ideal logistic operating curve

The ideal logistic operating curve is named ideal because it is developed on the basis of idealized production input data.

With ideal production the following assumptions are made:

1. There is only one order at a time,

2. The inter-operation time is zero, the order comes in and the work starts right away,
3. There is only one workstation,
4. The workstation maximum output is its maximum possible output rate,
5. The given orders cannot change after entering the system,
6. It is not possible to overlap the orders.

4.2 Calculating ideal level minimum work in process

First step is to calculate ideal minimum WIP level. It is calculated with following formula:

$$WIP_{min} = \frac{\sum_{i=1}^n (WC_i \cdot WC_i)}{\sum_{i=1}^n WC_i} \quad (19)$$

where WIP_{min} – ideal minimum WIP (hrs),

WC_i – work content per operation (hrs),

n – number of orders.

This equation takes into consideration, that the orders with bigger work content will take more time to produce, and the WIP will be bigger and the WIP will be used longer. However, additionally the ideal minimum WIP can be calculated with taking into consideration the distribution parameter. With equation:

$$WIP_{min} = WC_a + \frac{WC_s^2}{WC_a} \quad (20)$$

where WIP_{min} – ideal minimum WIP (hrs),

WC_a – average work content (hrs),

WC_s – standart deviation of work content (hrs).

Then if the equation 4 is combined with equation 20, the following equation will result:

$$WIP_{min} = WC_a \cdot (1 + WC_v^2) \quad (21)$$

where WIP_{min} – ideal minimum WIP (hrs),

WC_a – average work content (hrs),

WC_v – coefficient of variation for work content.

If we consider the transportation time between the operations in the calculations, the equation for the ideal minimum WIP level will be following:

$$WIP_{min} = \frac{\sum_{i=1}^n (WC_i \cdot WC_i)}{\sum_{i=1}^n WC_i} + \frac{\sum_{i=1}^n (TTR_i \cdot WC_i)}{\sum_{i=1}^n WC_i} \quad (22)$$

where WIP_{min} – ideal minimum WIP (hrs),

WC_i – individual work content per operation (hrs),

TTR_i – transportation time for operation (hrs).

The equation can be simplified, in case the transportation time is constant. This equation is used in this work's model:

$$WIP_{min} = WC_a \cdot (1 + WC_v^2) + TTR \quad (23)$$

where WIP_{min} – ideal minimum WIP (hrs),

WC_a – average work content (hrs),

WC_v – coefficient of variation for work content,

TTR – constant transport time (hrs).

The equation can be modified further if there are some inter-operation processes, like cooling down.

4.3 Calculating maximum possible output rate

While when calculating the ideal minimum WIP the maximum possible output rate was the workstation capacity. Actual maximum output rate depends not only on the machine machining time (which can change due to failures and other disturbances), but also on the availability of the operator's time (see Figure 24). Therefore, the maximum output rate will look like this:

$$ROUT_{max} = \min\{CAP_m, CAP_o\} \quad (24)$$

where $ROUT_{max}$ – maximum output rate (hrs/SCD),

CAP_m – available machine capacity (hrs/SCD),

CAP_o – available operator capacity (hrs/SCD).

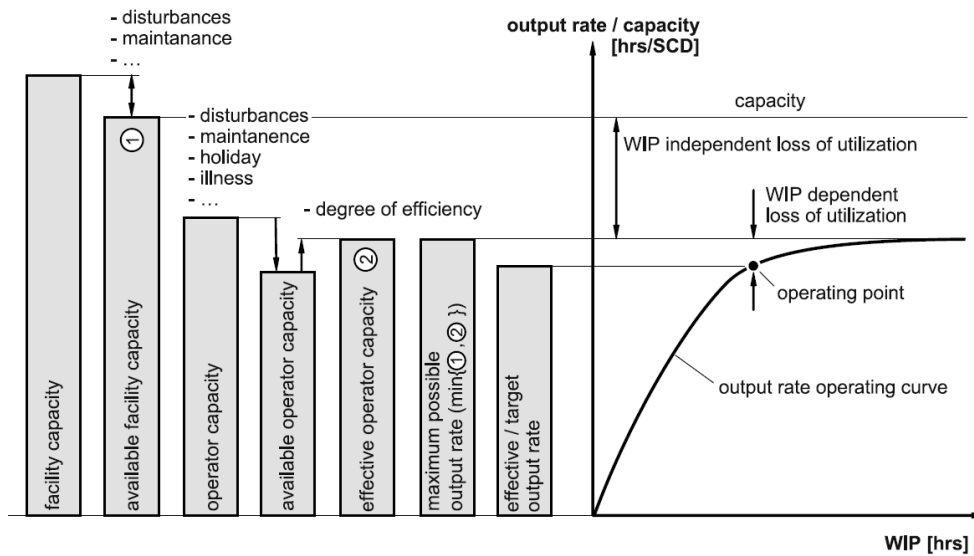


Figure 24. Output rate operating curve relation to the capacity [8, p 64]

4.4 Starting to build the logistic operating curves

The maximum output rate of a workstation can be calculated from the maximum output rate with the minimum work in process level.

After finding this point, then the output rate operating curves behaviour is described as follows: if the operation is disturbed due to some reason, the output is lowered proportionally to the lowering of WIP (on Figure 25 it's proportional operating zone); if the order amount for a workstation is increased, the WIP increases, but the output rate does not increase, because the station already works on a maximum possible rate (on Figure 25 it's saturated operating zone).

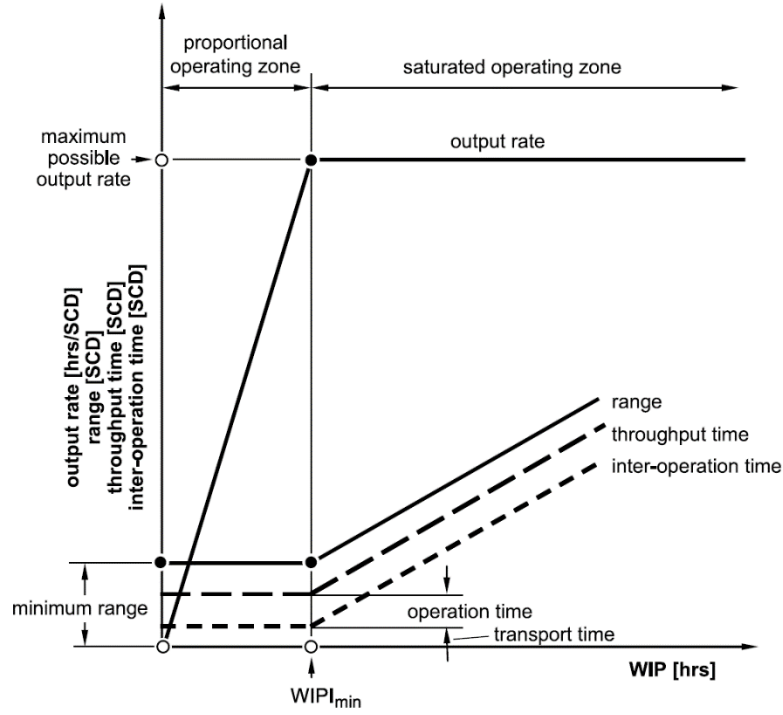


Figure 25. Building the output rate operating curve [8, p 65]

The behaviour of the Rate operating curve can be described as a relation between the WIP and output rate. Therefore, the range usually behaves the same as the WIP. However, if the WIP is lower than the ideal minimum WIP, range curve then is constant (as it was during the ideal minimum WIP, see Figure 25). So the minimum range can be calculated as:

$$R_{min} = \frac{WIP_{min}}{ROUT_{max}} \quad (25)$$

where R_{min} – ideal minimum range (SCD),

WIP_{min} – ideal minimum work in process (hrs),

$ROUT_{max}$ – maximum possible output rate (hrs/SCD).

If together with equation 25 are used equations 23, 5 and 6, then the following equation will be developed:

$$R_{min} = TOP_a \cdot (1 + TOP_v^2) + \frac{TTR_a}{ROUT_{max}} \quad (26)$$

where R_{min} – minimum range (SCD),

TOP_a – average operation time (SCD),

TOP_v – coefficient of variation of operation time,

TTR_a – average transportation time (hrs),

$ROUT_{max}$ – maximum output rate (hrs/SCD).

The throughput time minimum is set according to the operation time and where there is, the transportation time. The following equation for calculating it is used:

$$TTP_{min} = TOP_m + \frac{TTR_a}{ROUT_{max}} \quad (27)$$

where TTP_{min} – minimum throughput time (SCD),

TOP_a – average operation time (SCD),

TTR_a – average transportation time (hrs),

$ROUT_{max}$ – maximum possible output rate (hrs/SCD).

The minimum inter-operation time is related to the average transportation time and is calculated with the help of the equation:

$$TIO_{min} = \frac{TTR_a}{ROUT_{max}} \quad (28)$$

where TIO_{min} – inter-operation time (SCD),

TTR_a – average transportation time (hrs),

$ROUT_{max}$ – maximum possible output rate (hrs/SCD).

The ideal throughput and inter-operation time are build above the minimum WIP, parallel to the range operating curve.

4.5 Calculating output rate operating curve

For defining the points of the output rate operating curve is used the C_{norm} function (see Figure 26). It has a form of a generalization of the circle. The generalizing in this is replacing the value with an open parameter ‘C’, so the function, in all the coordinate system sectors, is true for every ‘C’.

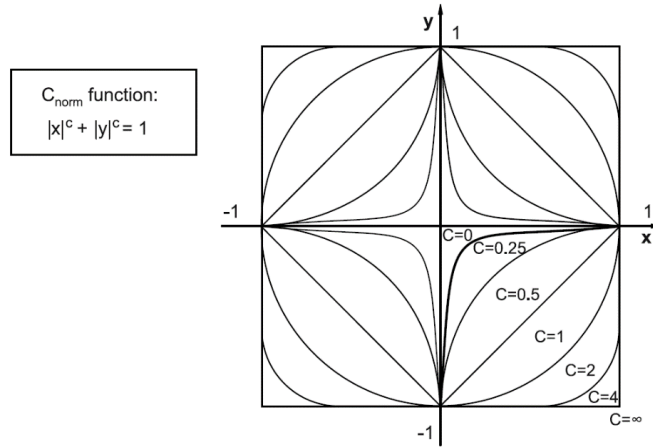


Figure 26. C_{norm} Function for various values of C [8, p 69]

As it is shown in the Figure 26, the curve with C value 0,25 is strongly resembles the output operating curve.

To mathematically describe this function the following equation is used:

$$\begin{cases} x(t) = t \\ y(t) = -\sqrt[C]{1 - t^C} \end{cases} \quad (29)$$

In Figure 27 is shown the calculation of points for the C_{norm} function with a C value chosen as 0,25. On this example 11 points, using equation 29 were calculated, where the $0 \leq t \leq 1$.

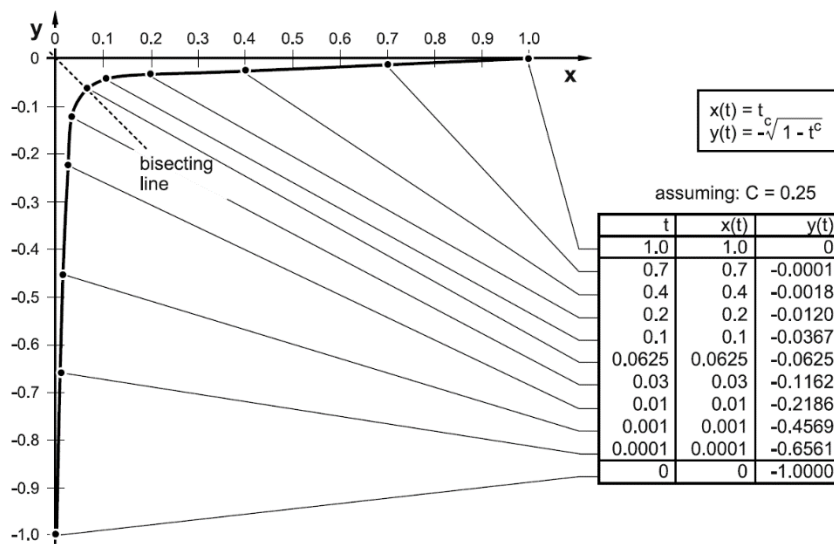


Figure 27. Building the C Function with C=0,25 [8, p 69]

After finding the basic function, it should be modified further so that it was related to output operating curve. This process is done in four steps (see Figure 28).

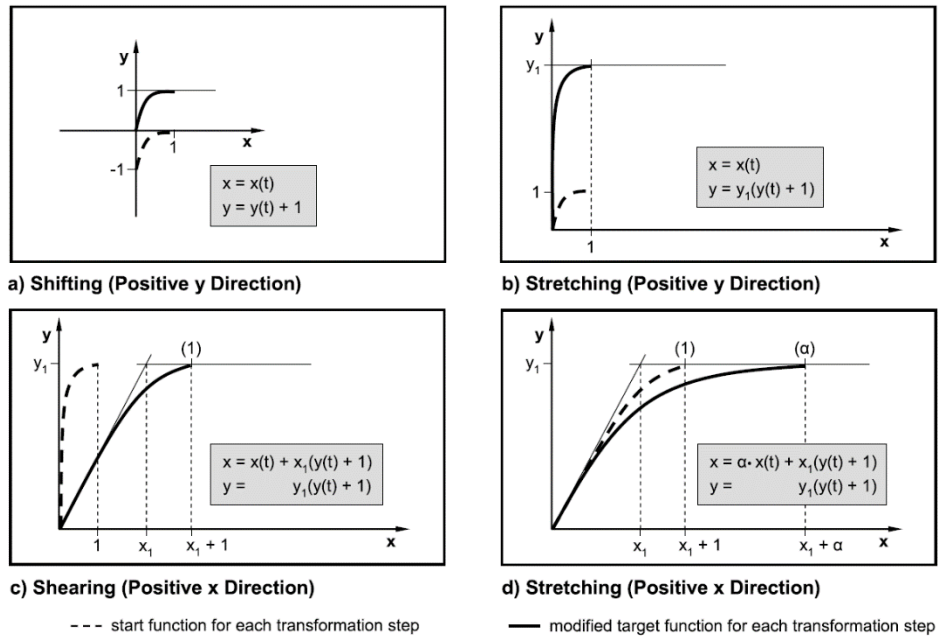


Figure 28. Steps done to create the output operating curve from C_{norm} curve [8, p 70]

Step one: shifting the curve in x-positive direction, so that the starting point of the curve was (0,0). To do that to each y is added 1 (see Figure 28, section a).

Step two: shifting the curve in y-positive direction, so that the y maximum was equal to the maximum output rate. Value of y is multiplied with stretch factor y_1 (see Figure 28, section b).

Step tree: shifting the point of angulation to the minimum WIP level, x_1 . Additionally to that point, all other x values must be changed (except the starting point). On Figure 28, section c is shown what is needed to do.

Step four: shifting the curve in the x-positive direction (see Figure 28, section d). For this is used the parameter Alpha (α). Parameter alpha represents the WIP buffer. The bigger is the ideal minimum WIP level, the bigger should be the WIP levels to ensure that the working station works constantly.

By changing the α parameter, the shape of the curve changes. Many testing trials were made with LOC models and it was estimated, that the default Alpha equals 10.

After we substitute equation 29 of C_{norm} function for $x(t)$ and $t(t)$, the form of the output rate operating curve is:

$$\begin{cases} x = x_1 \cdot (1 - \sqrt[c]{1 - t^c}) + \alpha \cdot x_1 \cdot t \\ y = y_1 \cdot (1 - \sqrt[c]{1 - t^c}) \end{cases} \quad (30)$$

To use equation 30 in calculating the output curve, following substitutions should be made:

1. $x(t)$ change to $WIP_a(t)$, where average WIP is the function of t ;
2. $y(t)$ change to $ROUT_a(t)$, where output rate is the function of t ;
3. x_l change to WIP_{min} ;
4. y_l change to $ROUT_{max}$;
5. C change to $1/4$, from C_{norm} function, where $C=0,25$.

After the changes, the equations to calculating the output operating points curve are:

$$\begin{cases} WIP_a(t) = WIP_{min} \cdot (1 - (1 - \sqrt[4]{t})^4) + WIP_{min} \cdot \alpha \cdot t \\ ROUT_a(t) = ROUT_{max} \cdot (1 - (1 - \sqrt[4]{t})^4) \end{cases} \quad (31)$$

where WIP_a – average WIP (hrs),

WIP_{min} – ideal minimum WIP level (hrs),

α – stretch factor alpha,

$ROUT_a$ – average output rate (hrs/SCD),

$ROUT_{max}$ – maximum possible output rate (hrs/SCD).

On basis of calculating the output rate operating curve, a few equation and parameters can be used and found.

One of them is following:

$$U_a(t) = \frac{ROUT_m(t)}{ROUT_{max}} \cdot 100 = (1 - (1 - \sqrt[4]{t})^4) \cdot 100 \quad (32)$$

where $U_a(t)$ – average WIP depending from the utilization (%),

$ROUT_a(t)$ – average output rate (hrs/SCD),

$ROUT_{max}$ – maximum output rate (hrs/SCD),

t – running variable ($0 \leq t \leq 1$).

The parameter of average WIP from equation 30 can be divided to two components:

$$WIP_a(t) = WIP_{aa}(t) + WIP_{ab}(t) \quad (33)$$

$$WIP_{aa}(t) = WIP_{min} \cdot (1 - (1 - \sqrt[4]{t})^4) = \frac{WIP_{min} \cdot U_a(t)}{100} \quad (34)$$

$$WIP_{ab}(t) = WIP_{min} \cdot \alpha \cdot t \quad (35)$$

where $WIP_a(t)$ – average WIP (hrs),

- $WIP_{aa}(t)$ – average active WIP (hrs),
- $WIP_{ab}(t)$ – average buffer WIP (hrs),
- WIP_{Imin} – ideal minimum WIP (hrs),
- $U_m(t)$ – average WIP dependant form utilization (%),
- α – stretch factor,
- t – running variable ($0 \leq t \leq 1$).

One of the components of work in process, $WIP_{aa}(t)$ results from the orders that are being processed. This component should be equal or less than the ideal minimum WIP. Another component, $WIP_{ab}(t)$ showing the queued orders, and can be called as a buffer. In reality to increase the utilization rate, big WIP buffers are maintained. But if the company can lower the utilization a little bit, for example on 3,5%, then the amount of WIP can be greatly decreased.

Stretch factor Alpha is a representation of this process. The default stretch factor alpha, which equals 10 shows that the utilization was lowered 3,5% due to some reasons. Usually in real production it is so, it is not possible for a person to work always 100%, so the utilization fluctuates. To make the model results more similar to reality, the stretch factor α can be changed according to the situation in production.

To develop an equation that will be used for building the output rate operating curve without the function of (t), a few modification must be made. The equation 32 is solved, and the result will be:

$$t = \left(1 - \sqrt[4]{1 - \frac{U_a}{100}}\right)^4 \quad (36)$$

where U_a – average WIP depending from utilization (%),

t – running variable ($0 \leq t \leq 1$).

By changing equation 31 with equation 36, we can get:

$$WIP_a(U_a) = WIP_{Imin} \cdot \frac{U_a}{100} + WIP_{Imin} \cdot \alpha \cdot \left(1 - \sqrt[4]{1 - \frac{U_a}{100}}\right)^4 \quad (37)$$

$$WIP_a(ROUT_a) = WIP_{Imin} \cdot \frac{U_a}{100} + WIP_{Imin} \cdot \left(1 - \sqrt[4]{1 - \frac{U_a}{100}}\right)^4 \quad (38)$$

where WIP_a – average WIP (hrs),

WIP_{min} – ideal minimum WIP (hrs),

α – stretch factor Alpha,

U_a – average utilization ($0 < U_a < 100$) (%),

$ROUT_a$ – average output rate ($0 < ROUT_a < ROUT_{max}$) (hrs/SCD),

$ROUT_{max}$ – maximum output rate (hrs/SCD).

4.6 Calculating range operating curve and throughput time operating curve

There is a few ways to build a throughput operating curve. One is to use C_{norm} function like in case of output rate curve, and another is to define the throughput operating curve using the already existing output rate operating curve.

The first step is to use funnel formula (equation 16). From it follows the relation between $WIP_a(t)$ and $ROUT_a(t)$. The following equation can be formulated:

$$R_a(t) = \frac{WIP_a(t)}{ROUT_a(t)} \quad (39)$$

where $R_a(t)$ – average range (SCD),

$WIP_a(t)$ – average WIP (hrs),

$ROUT_a(t)$ – average output rate (hrs/SCD).

With the help of equations 26 and 27, the difference between the two values R_{min} and TTP_{min} describe the distance between the curves:

$$R_{min} - TTP_{min} = TOP_a \cdot TOP_v^2 \quad (40)$$

where R_{min} – minimum range (SCD),

TTP_{min} – minimum throughput time (SCD),

TOP_a – average operation time (SCD),

TOP_v – coefficient of variation of operation times.

So the throughput time operating curve is:

$$TTP_a(t) = R_a(t) - TOP_a \cdot TOP_v^2 \quad (41)$$

where $TTP_a(t)$ – average throughput time (SCD),

$R_a(t)$ – average range (SCD),

TOP_a – average operation time (SCD),

TOP_v – coefficient of variation for the operation time.

After applying the formulas to the Excel cells and getting needed points, the logistic operating curves graph can be constructed

5. Creating a schedule with logistic operating curves

To create a schedule and to test the usability of the logistic operating curves method, company has provided the example data of their projects. Inside the data there is no schedule. Besides the production operations and production times, the schedule can be created as we want. In table 2 is a short description of 12 project the company have provided for the analysis.

Table 2. EXTREME-MET example projects


Project code/number and short description	Project visual example
TL_0207-01 Material separating gate on belt conveyor	
TL_0408-01 Covers the side of the bridge (air shaft ventilation grid)	
TL_0414-01 Buss stop	

Table 2 (continuation). EXTREME-MET example projects

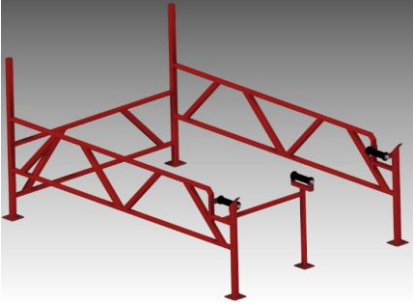

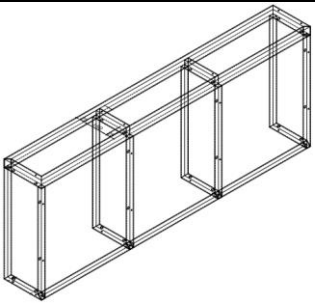




<p>TL_0422-01</p> <p>Frame that feeds the conveyor with wood logs</p>	
<p>TL_0513-01</p> <p>Buss stop</p>	
<p>TL_0514-01</p> <p>Frames for tables</p>	
<p>TL_0514-02</p> <p>Buss stop</p>	<p>No picture</p>
<p>TL_0514-03</p> <p>Advertising post</p>	

Table 2 (continuation). EXTREME-MET example projects

<p>TL_0627-01</p> <p>Lattice that covers air sides of a bridge</p>	
<p>TL_0708-02</p> <p>Buss stop</p>	
<p>TL_0708-02</p> <p>Buss stop</p>	<p>No picture</p>
<p>TL_0923-01</p> <p>Tank for bio waste</p>	

As the task is to create the schedule for all 12 projects without any constraints and any data from previous period, the starting point should be to recognize the bottleneck. For that, all the operation times should be compared.

The production of EXTREME-MET consists of 10 employees. Some operations are done by several operators and others singular, but as the production times that were provided are consisting from the time that was used for this operation (with however many people this operation usually is done) and is independent from amount of workers, so it will be named as one working station, with one operator, 8 working hours per day and 5 working days per week.

In Figure 29 are shown the operations names and times for each project. The working stations are highlighted with different colours. With bright red is shown the operation that is outsourced.

TL_0207-01	Sawing	2	Welding	35	Cleaning	5							
TL_0408-01	Drilling/thread cutting	120	Assembly/welding	214	Cleaning	8							
TL_0414-01	Sawing	5	Drilling	6	Bending	6	Assembly/welding	16	Galvanization week 1,5	Final assembly	16	Installation	11
TL_0422-01	Cutting	0,5	Turning	8	Sawing	2	Assembly/welding	7	Painting	1			
TL_0513-01	Sawing	8	Drilling	8	Bending	6	Assembly/welding	16,5	Galvanization week 1,5	Final assembly	16		
TL_0514-01	Sawing	40	Drilling	80	Assembly/Welding	115	Grinding	17					
TL_0514-02	Sawing	6	Drilling	8	Bending	6	Assembly/welding	18	Galvanization week 1,5	Final assembly	20		
TL_0514-03	Cutting	8	Sawing	8	Assembly/welding	110	Grinding	8					
TL_0627-01	Sawing	8	Drilling/Thread cutt	45	Assembly/welding	75	Cleaning	9					
TL_0708-02	Sawing	10	Drilling	20	Bending	12	Assembly/welding	40	Galvanization week 1,5	Final assembly	24	Installation	53
TL_0726-02	Sawing	6	Drilling	8	Bending	10	Assembly/welding	28	Galvanization week 1,5	Final assembly	16		
TL_0923-01	Sawing	64	Assembly/Welding	180	Cleaning/Grinding	6							
	Sawing	159											
	Cutting/Bending	48,5											
	Drilling	303											
	Cleaning/Grinding	53											
	Assembly/welding	854,5											
	Final assembly etc	157											
	Galvanization/Painting	280	Outsourcing										

Figure 29. The operations and times for every project in hrs

The sum of times for each operations of 12 projects shows that the bottleneck is the welding station. The time this operation takes is double the amount the next bottleneck takes. So this operation will be scheduled to test the logistic operating curves model.

5.1 Schedule 1

The logistic operating curve model in Excel was modelled, using the equation described in chapters 3 and 4. It consists from 6 spreadsheets. First is the input data sheet can be seen in Annex 1. With dark green colour are highlighted the cells that are being calculated with formulas and should be not touched.

With the light colour are indicated the cells that needed to be filled. It is the number of order, input day of the order, output day of the order. The days should be inserted in shop

calendar days. The number of the day is not important in our case, as this is the testing of the model, and there is no previous data. Let the first day of order input be 90.

On the right is the table that shows the parameters of a workstation. Name, the quantity of workers, capacity (the length of a shift). Also on this page, the stretch factor Alpha (more about it can be read from chapter 4) can be change. On default it is 10.

By hand should be filled the cell with work content that was inputted in the system, and also the work content that was left from previous period, it is orders that were not completed the previous period. Next cell is inter-operational time, which is usually zero, because it is not measured and usually includes already inside the operation time.

For schedule 1 the rough production plan was made by very rough estimation. It was made just to test the model, to see what will happen if the numbers are inputted.

The input data for schedule 1 can be seen in Annex 1. As could be notices, there is more orders than 12. It is so due to the amount of work content, as smallest work content of an order is 7 hours, and the biggest is 214 hours, the difference is quite big, and due to that the planning and analysing can be difficult. Therefore, the bigger orders, over 40 hours were divided into smaller.

Next sheet that was done during the development of the Excel file and it is the calculation sheet for throughput diagram. In Annex 2 is shown the part of calculations. On the right is the calculating's for the points from which the throughput diagram consist. As the reference period for this station is quite big (123 days), the calculations are continuing up to row 250. Therefore, while using this Excel file, it is important to remember that the limit of the throughput diagram calculations is 123 days, beginning from first output day until the last. This interval can be larger if the rows are copied and pasted at the end of the present calculations, but still amount of orders should be limited to the light green area of the input data sheet, and now it is 26 rows. On the left of the throughput calculations sheet, the table is just for help calculations.

After building the chart while using the points that were calculated on this page, the throughput diagram is constructed. From this diagram that is shown on Figure 30, some conclusions can be drawn.

First, is that the station is under loaded. It can be seen from the input curve that is drawn with red colour, it is below the capacity curve, that is shown with green. Also the output curve, shown with blue colour is far below capacity, the curve that is drawn with green.

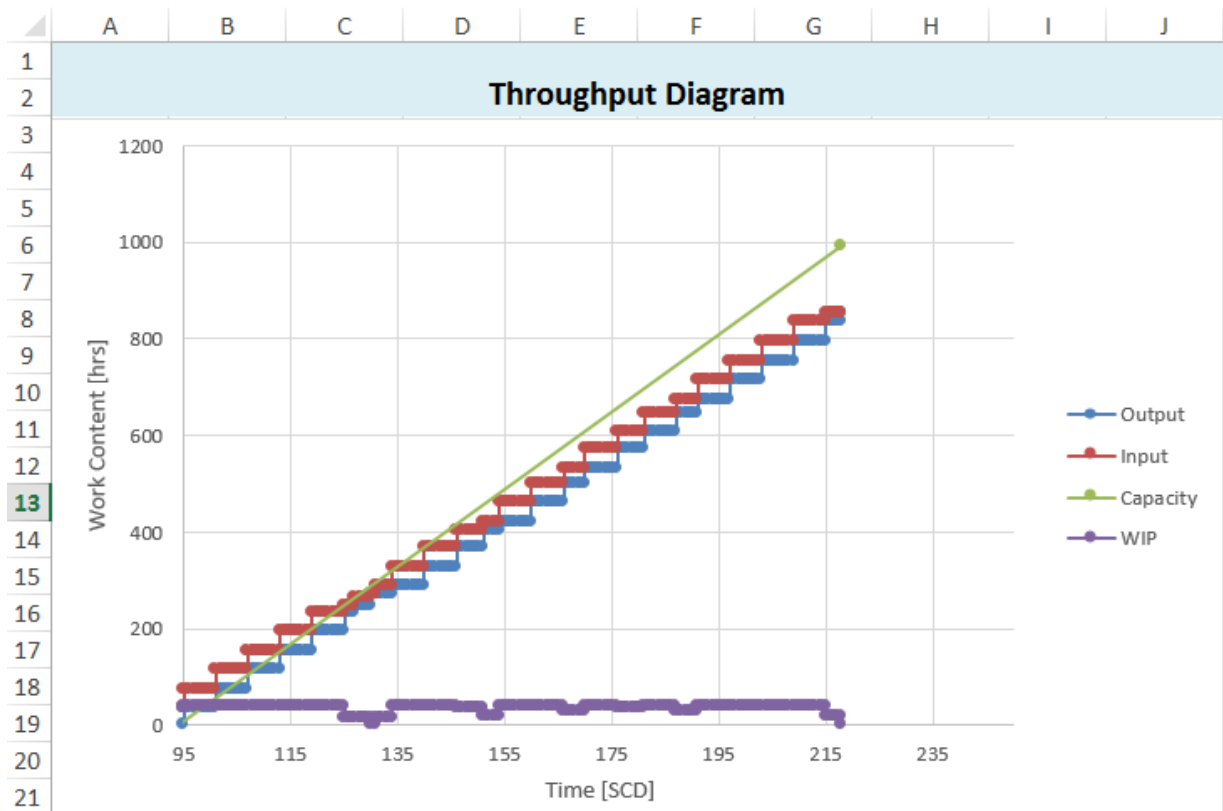


Figure 30. Throughput diagram for schedule 1

After the throughput diagram calculations are the logistic operations curves calculations. In Annex 3 is shown, how the Excel sheet with the calculations looks like. The first table to the left consist of the workstation details that were inputted and other parameters that were calculated with the help of equation from chapters 3 and 4.

The logistic operating curves points are calculated in the second table. As the logistic operating curves are showing the generalized picture of the station, the number of point is usually set. Therefore, if the period is changed, the calculations will still work. The only condition is that the inputted data should be inside the green area of the input data sheet, so that the orders were inside the range that is being calculated.

After the points were calculated, the chart with logistic operating curves is created. The Figure 31 shows how they look like. On the top is the original chart as it was created, but due to amount of data, the intersection between the logistic operating curves is not clearly seen. It is easily correct by changing the axis settings.

From the chart it is seen, that the operating point for this working station is not optimal. It is under loaded and the output rate and the throughput time could be higher, if the operating point is moved right on the chart.

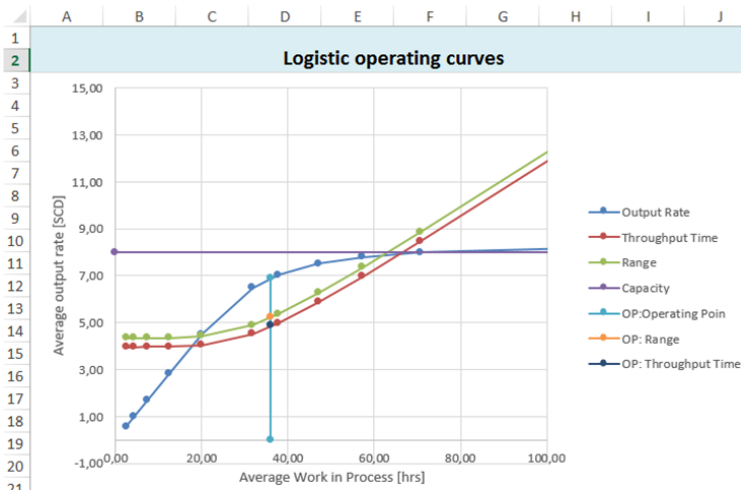
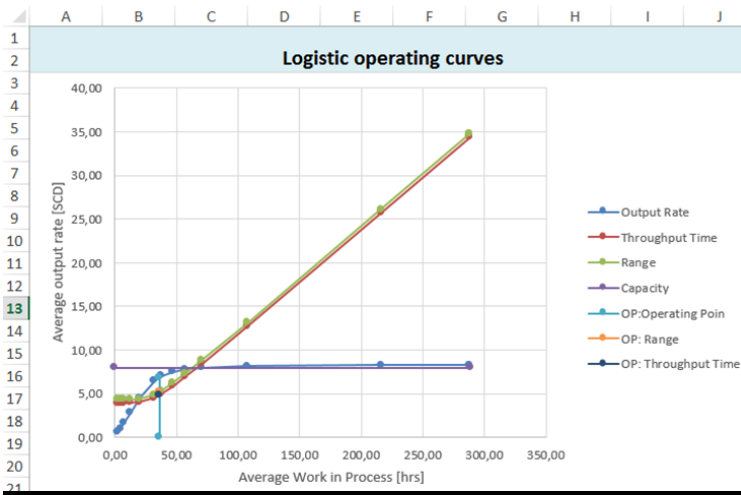


Figure 31. Logistic operating curves with unadjusted and adjusted axis for schedule 1

Last spreadsheet is the overview sheet that could be seen in Annex 4. There are shown the most important parameters for the work station analysis and shown the throughput diagram with LOC model again.

For schedule 1, the most critical parameters that should be paid attention are the utilization rate and maximum output rate.

The utilization rate for schedule 1 equals 82,4%, while the maximum output rate is the 8,43 hrs/SCD, which is above the capacity level of 8 hours.

The conclusion is that the schedule should be revised and changed.

And firstly, the utilization rate should be paid attention to.

5.2 Schedule 2

After the 1 schedule, it was revised and changed were applied. The input date and output date were changed, so that the throughput time is shortened to increase the utilization rate.

In Annex 5 is shown the modified schedule, the period is now 8 days shorter.

On Figure 32 is shown the throughput diagram for the changed schedule. As it shows, the utilization of workstation became higher, but still it could be better. After the throughput diagram, logistic operating curves should be analysed.

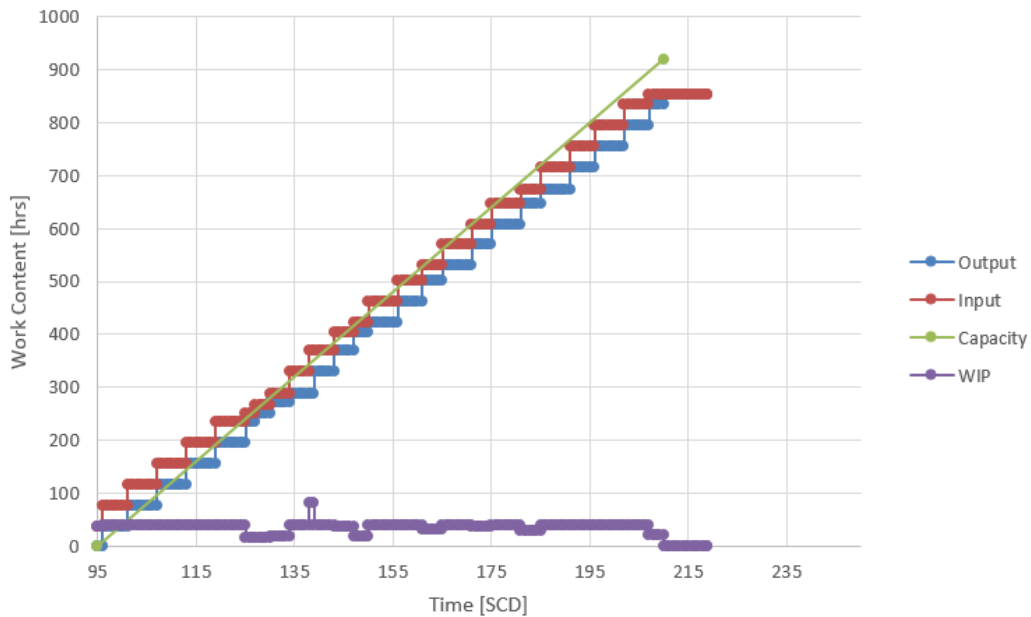


Figure 32. Throughput diagram for schedule 2

The logistic operating curves for the change schedule on Figure 33 shows, that the operating point for the workstation have shifted more to the right, but it is not yet optimal, it is possible to move it more.

In Annex 6 could be seen the overview sheet for schedule 2.

From it is seen, that the parameter of the maximum output rate shows the value of 9,23 hrs/SCD. It means, that some output date is set in overload zone. The output on that day is much higher than the capacity of 8 hrs.

The conclusion, the schedule should be modified again.

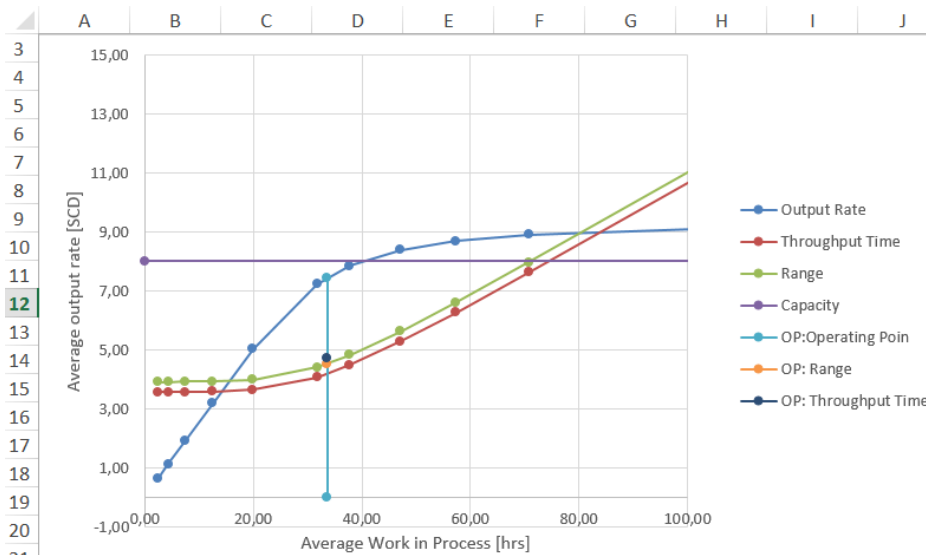


Figure 33. Logistic operating curves of schedule 2

5.3 Schedule 3

This time, to change the schedule, and make it more optimal, the points from which the throughput diagram consists are revised. For that it is better to adjust the axis of the throughput diagram, so that the data is seen better. On the Figure 34 is shown the schedule 2 of a period from day 95 to 115, on the throughput diagram.

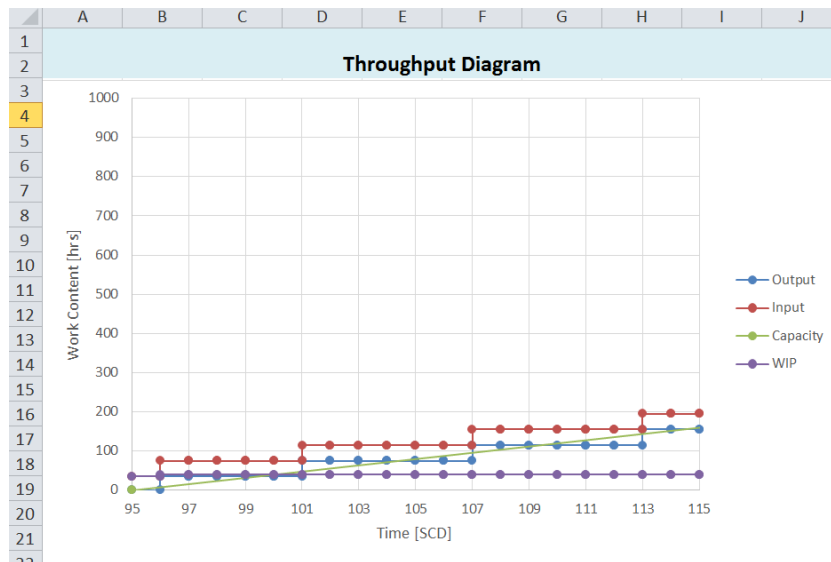


Figure 34. Revising period day 95-115 from schedule 2 on the throughput diagram

From it can be seen, that on day 96 the output point is higher than the green curve, for capacity, so we must move it a few days later. The same with output day 101, and 107, and also 113. The input points also should be moved. For example, on day 107 the red input curve is too close to the green capacity line.

After the changes in schedule, for period 95-115 the throughput diagram will look like this:
Figure 35.

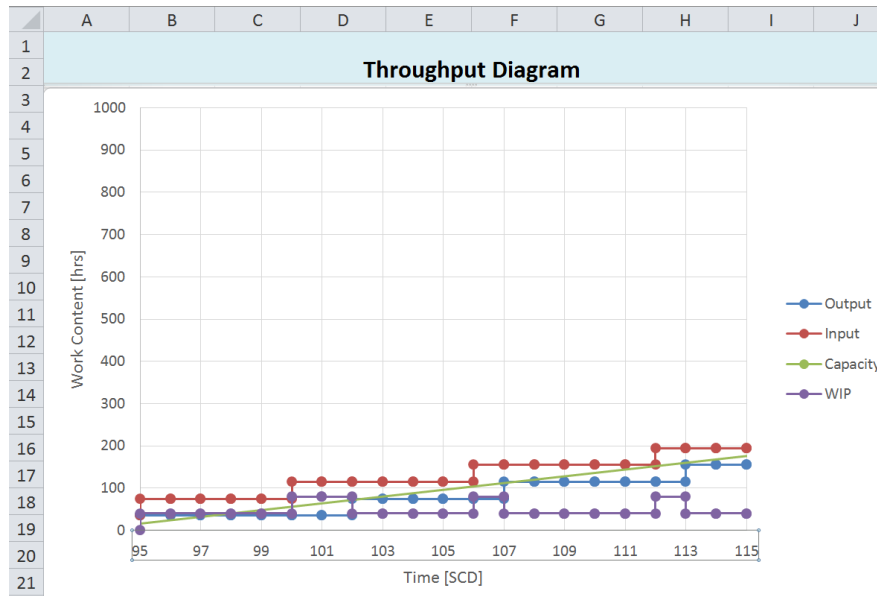


Figure 35. Schedule 3 for time period 95-115 shown on throughput diagram

After that, the review period should move to later date, to see the point more clearly. The principle of this revision is to move the output points more near green capacity curve, but not pass it, and to keep the red input rate curve points above green capacity line.

After all the changes, the throughput diagram for the schedule 3 will look better (see Figure 36).

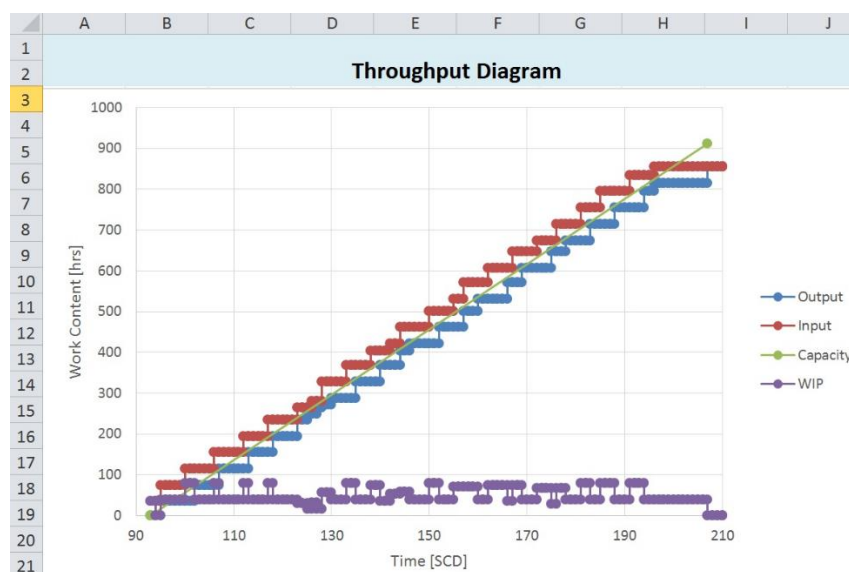


Figure 36. Throughput diagram for schedule 3

On Figure 37 can be seen the workstation situation. The operation point is not above capacity level, the average output rate is 7,5 hrs/SCD, which is quite good, only half an hour short of the maximum capacity.

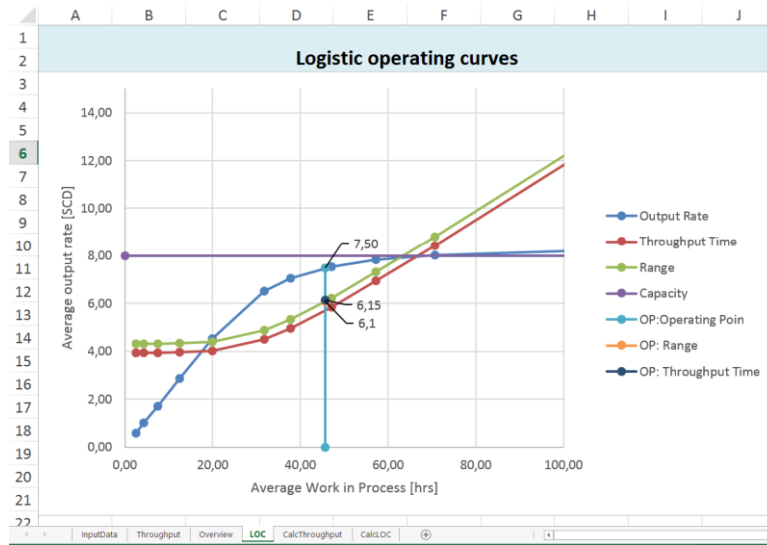


Figure 37. Logistic operating curves for schedule 3

The overview Excel sheet (see Annex 7) shows that the time period compared to the schedule 2, is one day less. However, the average output time have risen, and the utilization rate is now 90%.

The maximum output rate is 8,33 hrs/SCD, which is still higher than the capacity, but not much. Most probably some output point is a little bit higher than the green (capacity) curve, and could found and corrected, but it is not so critical as it was in case of schedule 2.

The schedule 3 for production is quite balanced and could be used in real production. In Annex 8 can be seen the schedule in shop calendar days. It could be notices, that almost all of the orders input dates are overlapping with the previous order output date. It lengthens the throughput time of an order, but due to this overlapping, it is possible to keep the WIP above the ideal minimum level and the input curve above or on the maximum capacity level, and not below.

Conclusion

Creating a schedule for production is a problem not only for big companies. All manufacturing companies are trying to optimize their processes, to use resources in efficient way, eliminate waste and reduce costs, and to do that a very important factor is a good, balanced schedule for production.

Small and medium companies also have this problems. To plan the usage of resources correctly, tools are needed. The most popular tool for planning the manufacture is the usage of special software. However, for small and medium companies it is too expensive, or to use it, special skills are needed.

To enable also small companies to have effective tool for planning of production, it is possible to create the logistic operating curves model. It will show the state of a station, or a line, according to it's capacity, work content, input and output date of an order.

The implementation efforts needed for it are minimal. For a person with engineering background, to get familiar with the calculations required for creating the LOC model, and then to create it in a spreadsheet program will take around 1- 2 weeks, depending on the familiarity with the equation used inside the logistic operating curves. If it is used by industrial engineer, then almost all equation will be familiar for this person, because the equation used in calculating the LOC are taken from the basic formulas from the field of operations management.

The model could be also created with such software as Microsoft Excel, but it could be also done with the free software that is available online, OpenOffice.

The logistic operating curves and the parameters that are calculated together allow to draw conclusion about the workstation state. Is it under loaded, or overloaded, is the operating point in the optimal state.

With the help of the logistic operating model it is possible to make a balanced schedule, without big efforts. For that it is only needed to understand what each curve means, how they must look like in optimal state and which data to change in order to influence the look of the graphs.

With short explanations a person, who have not studied the logistic operating curves modelling method in deep details, can use the model also.

Summary

The production planning is a problem for many enterprises. Some do not pay enough attention to it, others do not really know how to correctly plan it, or do not have tools to do it. It is often occurred problem for all manufacturing companies, independent from their size.

In Estonia from all the amount of companies there are, 99,9% is small and medium enterprises. From the number of small and medium enterprises, 73% of them have one or more workers and bringing to their owner a profit.

It means that for a country it is very important to support small and medium enterprises for the sake of the economy growth.

On the example of small metalworking company, EXTREME-MET, a tool for production planning was chosen and developed.

From three tools that are usually used for the production planning and creating a schedule, one was chosen. It is logistic operating curves. It is a method developed in Germany, but as of yet not very known outside of Germany.

The logistic operating curves method is a simple tool, based on the basic formulas from operations research field; it is calculated with the help of a spreadsheet program. The result is seen as a chart that shows the state of a workstation, and important parameters, that are calculated for it. For example, maximum output rate, average output rate, ideal minimum WIP level and so on. It will enable not only to create a schedule, but also to plan the optimal usage of resources and the utilization rate of a workstation.

For calculating the logistic operating curves, Microsoft Excel spreadsheet can be used, or a free software with similar features, Open Office. That makes this method affordable for all companies, independent from its size.

The implementation efforts for this tool are minimal. To develop it, it takes for industrial engineer around one week, for person who is not familiar with concepts and formulas from operations research field, it can take longer, maybe two weeks or more.

However, after the model is completed, any person can use it after the explanation, what the charts and parameters are showing.

With the data from EXTREME-MET company, a production schedule was created. It was done for experimenting purpose, to test the usability of the logistic operating curves model.

However, the test of this model should be continued in real production. As of now, it was shown, that it is possible to use logistic operating curves, but it still should be tested in everyday production for planning and scheduling everyday production activities.

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Annex 1

	A	B	C	D	E	F	G	H	I
	Order number	Input date (SCD)	Output date (SCD)	Work Content (hr)	Through put time (SCD)		Workstation name	Welding/Assembling	
1	TL_0207-01	90	96	35	6		Number of Workstations	1	
2							Capacity for Single workstation	8 hrs/SCD	
3	1TL_0408-01	95	101	40	6		Minimum Inter-Operation Time	0 hrs	
4	2TL_0408-01	101	107	40	6		Capacity	8 hrs	
5	3TL_0408-01	107	113	40	6		Stretch factor 'Alpha'	10	0<Alpha<130
6	4TL_0408-01	113	119	40	6				
7	5TL_0408-01	119	125	40	6		Work in Process first day	35 hrs	
8	6TL_0408-01	125	127	14	2		Output prior evaluation period	0	
9	TL_0414-01	127	130	16	3				
10	TL_0422-01	130	130	7	0		Interoperational Time	0	
11	TL_0513-01	131	134	16,5	3				
12	1TL_0514-01	134	140	40	6				
13	2TL_0514-01	140	146	40	6				
14	3TL_0514-01	146	151	35	5				
15	TL_0514-02	151	154	18	3				
16	1TL_0514-03	154	160	40	6				
17	2TL_0514-03	160	166	40	6				
18	3TL_0514-03	166	170	30	4				
19	1TL_0627-01	170	176	40	6				
20	2TL_0627-01	176	181	35	5				
21	TL_0708-02	181	186	40	5				
22	TL_0726-02	187	191	28	4				
23	1TL_0923-01	191	197	40	6				
24	2TL_0923-01	197	203	40	6				
25	3TL_0923-01	203	209	40	6				
26	4TL_0923-01	209	215	40	6				
27	5TL_0923-01	215	218	20	3				
28									

Annex 2

	A	B	C	D	E	F	G	H	I	J	K
1	Day number	Output	Input	WIP		Start	96		WCav	WC	(WCav-WC)2
2	95	0	35	35		End	218		32,87	35	4,5369
3	96	0	35	35		Output prior Evaluation Period	0		32,87	40	50,8369
4	96	35	75	40					32,87	40	50,8369
5	97	35	75	40		Capacity Limit			32,87	40	50,8369
6	97	35	75	40			95	0	32,87	40	50,8369
7	98	35	75	40			218	984	32,87	40	50,8369
8	98	35	75	40					32,87	14	356,0769
9	99	35	75	40					32,87	16	284,5969
10	99	35	75	40					32,87	7	669,2569
11	100	35	75	40					32,87	16,5	267,9769
12	100	35	75	40					32,87	40	50,8369
13	101	35	75	40					32,87	40	50,8369
14	101	75	115	40					32,87	35	4,5369
15	102	75	115	40					32,87	18	221,1169
16	102	75	115	40					32,87	40	50,8369
17	103	75	115	40					32,87	40	50,8369
18	103	75	115	40					32,87	30	8,2369
19	104	75	115	40					32,87	40	50,8369
20	104	75	115	40					32,87	35	4,5369
21	105	75	115	40					32,87	40	50,8369
22	105	75	115	40					32,87	28	23,7169
23	106	75	115	40					32,87	40	50,8369
24	106	75	115	40					32,87	40	50,8369
25	107	75	115	40					32,87	40	50,8369
26	107	115	155	40					32,87	40	50,8369
27	108	115	155	40					32,87	20	165,6369
28	108	115	155	40							
29	109	115	155	40							
30	109	115	155	40							
31	110	115	155	40							
32	110	115	155	40							
33	111	115	155	40							
34	111	115	155	40							
35	112	115	155	40							
36	112	115	155	40							
37	113	115	155	40							
38	113	155	195	40							
39	114	155	195	40							
40	114	155	195	40							
41	115	155	195	40							
42	115	155	195	40							
43	116	155	195	40							
44	116	155	195	40							
45	117	155	195	40							
46	117	155	195	40							
47	118	155	195	40							
48	118	155	195	40							
49	119	155	195	40							
50	119	195	235	40							

Annex 3

	A	B	C	D	E	F	G	H	I	J	K	L
1	Workstation Details			Calculating the LOC								
2	w	1		t	Ua	Pa	lb	lp	la	Irel	Ra	LTm
3	CAP	8		0,0000001	6,93	0,58	2,50	0,00	2,50	7	4,27	3,90
4	ROUTmax	8,43		0,000001	12,06	1,02	4,35	0,00	4,35	12	4,27	3,90
5	Wca	32,87		0,00001	20,67	1,74	7,45	0,00	7,45	21	4,28	3,90
6	WCs	10,33		0,0001	34,39	2,90	12,39	0,04	12,43	34	4,29	3,91
7	WCv	0,31		0,001	54,31	4,58	19,57	0,36	19,93	55	4,35	3,98
8	TIOmin	0		0,01	78,14	6,59	28,15	3,60	31,76	88	4,82	4,45
9	WIPmin	36,03		0,02	84,84	7,15	30,57	7,21	37,78	105	5,28	4,91
10	ALPHA	10		0,04	90,66	7,64	32,67	14,41	47,08	131	6,16	5,78
11	C-Norm-	0,25		0,065	93,99	7,92	33,87	23,42	57,29	159	7,23	6,85
12				0,1	96,33	8,12	34,71	36,03	70,74	196	8,71	8,34
13				0,2	98,80	8,33	35,60	72,06	107,66	299	12,93	12,55
14	Reference period	123		0,5	99,94	8,42	36,01	180,15	216,16	600	25,66	25,28
15				0,7	99,99	8,43	36,03	252,21	288,24	800	34,19	33,82
16					99,99	8,43			288,24		34,19	33,82
17												
18	Ideal Output Rate OC			Calculation of ROUTmax with WIPrel-->Ua-->ROUTmax								
19		WIPa	ROUTa	Newtons approximation procedure								
20		0	0	t	F(t)	F'(t)	t(n+1)			WIPrel		
21		36,03	8,43	0,00000001	-0,95669536	5529087,406	0,00000002			97,9		
22		289,00	8,43	0,0000002	-0,89976855	110327,9734	0,0000083					
23	Capacity Limit			0,0000083	-0,7807325	5475,055565	0,0001509			Ua		
24		0	8	0,0001509	-0,60255095	526,2559435	0,001295905			82,4		
25		289,00	8	0,001295905	-0,39707567	87,8851095	0,005814027					
26	Operating Point			0,005814027	-0,19541746	28,01430361	0,012789658			Ra		
27		WIPa		0,012789658	-0,04515262	17,68758072	0,015342445			4,70		
28		35,3	0	0,015342445	-0,00195581	16,24333378	0,015462852			Tta		
29		35,3	6,95	0,015462852	-3,3959E-06	16,187075	0,015463062				5	
30		35,3	5,1	0,015463062	-1,0201E-11	16,18697775	0,015463062					
31		35,3	4,88									
32												

Annex 4

	A	B	C	D	E	F	G	H	I	J	
1	Throughput diagram										
2							26 number of completed orders				
3							32,87 hrs average work content				
4							10,33 hrs standart deviation work content				
5							4,88 SCD average throughput time				
6							5,08 SCD average range				
7							6,95 hrs/SCD average output rate				
8							8,43 hrs/SCD maximum output rate				
9							8 hrs/SCD capacity				
10							35,29 hrs average work in process level				
11							36,03 hrs ideal minimum work in process level				
12							97,9 % relative work in process				
13							82,4 % average utilization rate				
14							Lodistic operating curves				
15							122 SCD time period				
16											
17											
18											
19											
20											
21											
22											
23											
24											
25											
26											
27											
28											

Annex 5

	A	B	C	D	E	F	G	H	I
1	Order number	Input date (SCD)	Output date (SCD)	Work Content (hr)	Throughput time (SCD)		Workstation name	Welding/Assembling	
2	TL_0207-01	90	96	35	6		Number of Workstations	1	
3	1TL_0408-01	95	101	40	6		Capacity for Single workstation	8 hrs/SCD	
4	2TL_0408-01	101	107	40	6		Minimum Inter-Operation Time	0 hrs	
5	3TL_0408-01	107	113	40	6		Capacity	8 hrs	
6	4TL_0408-01	113	119	40	6		Stretch factor 'Alpha'	10	0<Alpha<130
7	5TL_0408-01	119	125	40	6				
8	6TL_0408-01	125	127	14	2		Work in Process first day	35 hrs	
9	TL_0414-01	127	130	16	3		Output prior evaluation period	0	
10	TL_0422-01	130	130	7	0				
11	TL_0513-01	130	134	16,5	4		Interoperational Time	0	
12	1TL_0514-01	134	139	40	5				
13	2TL_0514-01	138	143	40	5				
14	3TL_0514-01	143	147	35	4				
15	TL_0514-02	147	150	18	3				
16	1TL_0514-03	150	156	40	6				
17	2TL_0514-03	156	161	40	5				
18	3TL_0514-03	161	165	30	4				
19	1TL_0627-01	165	171	40	6				
20	2TL_0627-01	171	175	35	4				
21	TL_0708-02	175	181	40	6				
22	TL_0726-02	181	185	28	4				
23	1TL_0923-01	185	191	40	6				
24	2TL_0923-01	191	196	40	5				
25	3TL_0923-01	196	202	40	6				
26	4TL_0923-01	202	207	40	5				
27	5TL_0923-01	207	210	20	3				

InputData

Throughput

Overview

LOC

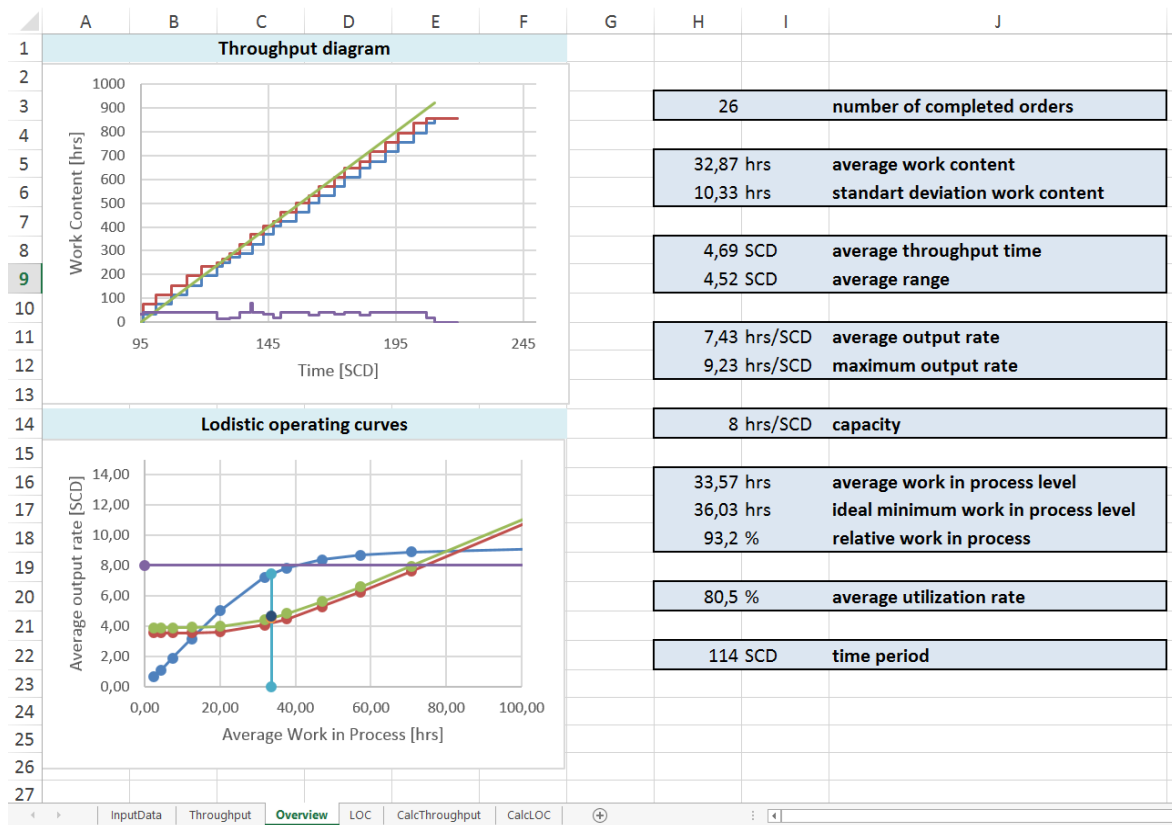
CalcThroughput

CalcLOC

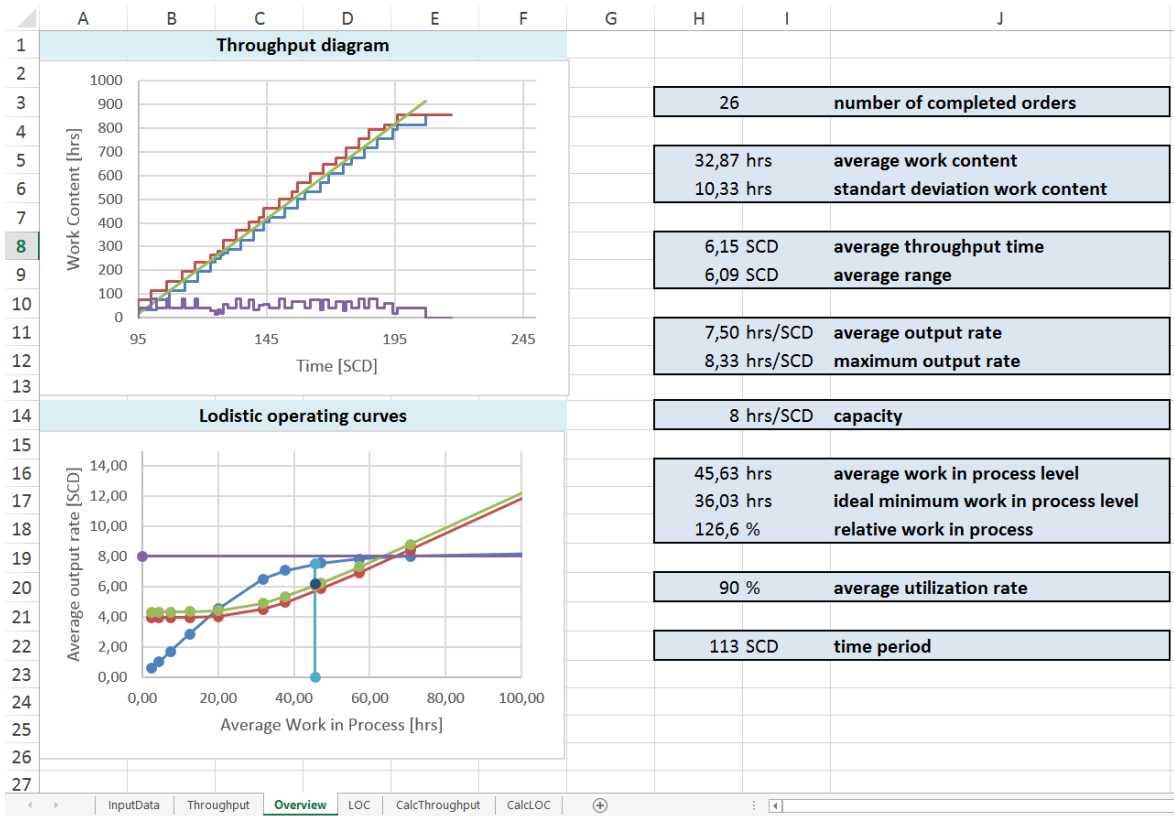
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Annex 6



Annex 7



Annex 8

	A	B	C	D	E	F	G	H	I
	Order number	Input date (SCD)	Output date (SCD)	Work Content (hr)	Through put time (SCD)		Workstation name	Welding/Assembling	
1	TL_0207-01	90	94	35	4		Number of Workstations	1	
2							Capacity for Single workstation	8 hrs/SCD	
3	1TL_0408-01	95	102	40	7		Minimum Inter-Operation Time	0 hrs	
4	2TL_0408-01	100	107	40	7		Capacity	8 hrs	
5	3TL_0408-01	106	113	40	7		Stretch factor 'Alpha'	10	0<Alpha<130
6	4TL_0408-01	112	118	40	6				
7	5TL_0408-01	117	123	40	6				
8	6TL_0408-01	123	125	14	2		Work in Process first day	35 hrs	
9	TL_0414-01	123	127	16	4		Output prior evaluation period	0	
10	TL_0422-01	128	128	7	0				
11	TL_0513-01	126	130	16,5	4		Interoperational Time	0	
12	1TL_0514-01	128	135	40	7				
13	2TL_0514-01	133	140	40	7				
14	3TL_0514-01	138	144	35	6				
15	TL_0514-02	142	146	18	4				
16	1TL_0514-03	144	152	40	8				
17	2TL_0514-03	150	157	40	7				
18	3TL_0514-03	155	160	30	5				
19	1TL_0627-01	157	166	40	9				
20	2TL_0627-01	162	169	35	7				
21	TL_0708-02	167	175	40	8				
22	TL_0726-02	172	178	28	6				
23	1TL_0923-01	176	183	40	7				
24	2TL_0923-01	181	188	40	7				
25	3TL_0923-01	185	194	40	9				
26	4TL_0923-01	196	207	40	11				
27	5TL_0923-01	191	196	20	5				
28									
29									
30									