



CHALMERS
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BSc's Thesis

Flexible production concept for the automotive industry

Proceeding from dedicated production flows towards increased flexibility to meet the demand of tomorrow

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CHALMERS TEKNISKA HÖGSKOLA | CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sverige 2023 | Gothenburg, Sweden 2023
www.chalmers.se

Flexible production concept for the automotive industry

Proceeding from dedicated production flows towards increased flexibility to meet the demand of tomorrow

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Aurobay (Powertrain Engineering Sweden AB)

Chalmers University of Technology

Göteborg, Sweden 2023

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Abstract

Aurobay is an automotive powertrain supplier and originates from Volvo Car Cooperation. The company has production sites in Skövde, Sweden, and in Zhangjiakou, China. Today automotive industry is in a redefine phase with new emission legislature and new technologies requiring automotive manufactures to be fast in order to adapt. One way is by being flexible.

The project team has, with the DMAIC methodology, examined several low volume flexible production concepts for manufacturing of cylinder heads (CH), cylinder blocks (CB) and mass balancing system (MBS). When defining the project scope. Did the project team learn that the question “what is flexibility?” and “what is prioritised in flexible production concept?” needed to be addressed.

During the define phase, voice of the customer disclosed the need of a new ways of machining the products as well as new perspectives and approaches. Boundaries of were identified accordingly as volume of ranging between 10 000 to 30 000 units, no R&D, i.e., product development, and the product range consist of VEP and VED CB and CH generation 1 and 3 plus MBS.

In the measure (M) phase was the qualitative tool interviews used to collect data about flexibility but also validated with agreement analysis and hypothesis testing.

The output displayed that the assembly department had a common picture of flexibility and what to prioritise to succeed meanwhile support function and the machining department had a more various picture.

Conclusions drawn from simulated the concept was that utilisation rate is low and lot of non-value adding time. This is mainly caused by high set-up time, the complexity in job-shop and met the demand of flexibility. By removing variants ZPI could not handle can the production be a more standardise process and set up time decrease to less than 35% of working time.

The edge of knowledge is moved forward but to implement flexible concept is future research concerning standardisation and multifunctional tools needed to meet the demand of tomorrow.

Extended abstract

Aurobay is an automotive powertrain supplier and originates from Volvo Car Cooperation. The company has production sites in Skövde, Sweden, and in Zhangjiakou, China, and the headquarter is situated in Gothenburg, Sweden (Powertrain Engineering Sweden AB, 2022). Currently powertrains are delivered to Volvo Cars and Geely Holding from dedicated production flows. At the moment is the automotive industry in a redefined phase with electricity and new fuel solutions that will demand flexible production flow.

The Skövde plant has profound history of manufacturing powertrain components. From starting as *Pentaverken* in the 1910s and delivering the very first Volvo engine and has developed into global actor of the 21st century. Undertaking major challenges during the years have the plant proved itself, such as becoming one of the first climate neutral automotive factories in the world.

The project team has, with the DMAIC methodology, examined several low volume flexible production concepts for manufacturing of cylinder heads (CH), cylinder blocks (CB) and mass balancing system (MBS). In the define (D) was first the question “*what is flexibility?*” and “*what is prioritised in flexible production concept?*”. These questions become important throughout the thesis work.

Further on, in the define phase did the voice of the customer disclose the need of a new ways of producing these products as well as new perspectives. The desired outcome and project benefits from were identified as improved ability to meet customer demand, increased equipment utilisation, flexibility understanding and mapping of products. Moreover, boundaries are another part of define and in this thesis work the volume is 10 000 to 30 000 units, no R&D (research and development), i.e., product development, and the product range consist of VEP and VED CB and CH generation 1 and 3 plus MBS.

In the measure (M) phase interviews was used as the qualitative tool to collect data about flexibility in production among several departments at Aurobay, but also at Volvo Tuve. The Volvo truck factory in Tuve had good flexibility by pushing out variation from the main flow and a low grade of automation. The collected data was amassed in a kinship chart that presented standardisation, system thinking, takt and department culture are four elements for success in flexible production. In parallel did were production philosophies and flexible production studied, as well as information about each step required to produce the products were collected.

The collected data regarding flexibility was (A) analysed with agreement analysis and hypothesis testing. The output displayed that the assembling department had a common picture of flexibility and what to prioritise to succeed meanwhile support function and the machining department had a more various picture. Furthermore, when analysing the inputs needed for generating concepts, the bill of process (BOP) was useful for mapping products constraints and similarities and the value stream mapping proved to have important information for takt calculations etc. By gathering BOP- and VSM data, a job-shop inspired layout with principles such as First in first out (FIFO), pull flow and with balanced degree of automation, could simulations on different concept ideas be done.

The team could after analysing the collected data present a flexibility definition:

“A flexible concept is well standardised and the people and machines within and around the concept are organised for handling variation in volume and products. Machines are likewise capable of manufacturing multiple variants and products. The concept is ready for adaptation as well as redefinition of new strategies for meeting the market demand. Flexible concepts are built with a system thinking and can handle change in culture, workforce and management”

A flexibility concept definition that the project team together with analysis of the collected data could build concepts.

The concepts ideas are:

1. Three parallel lines with 10 000 products each. One for MBS, one for CB Volvo engine petrol (VEP) gen 1 and one for CH Volvo engine diesel (VED) gen 3.
2. One line combining the three products MBS, CB VEP gen 1 and CH VED gen 3 with 30 000 units in total yearly volume.
3. One line with capability of manufacturing both VED and VEP CH, both generations, and CB, generation three. The volume is spread out evenly on all variants and products.

Conclusions from the three concepts:

Concept one: The utilisation rate is low and lot of non-value adding time. MBS is optimised at $WIP = 3$, but and CH and CB at $WIP = 6$, and to reach the desired jobs per hours (JPH). By increasing the WIP, the required availability lower, but lead-time increased.

Concept two: The concept did not reach the required JPH at 21. However, the margin was small and at $WIP = 12$ was $JPH = 20,9$ achieved but is likely sensitive to disturbance. Still, value adding time is low and 90% of the worktime goes to setup time.

Concept three: This concept could perform JPH 10,5 which is only halfway to reach demanded JPH and with higher WIP lead to higher lead-time in this concept. By removing the variants ZPI could not handle it was a more standardise process and set up time reduced to less than 35% of working time.

However, possible improvement would be to push out variation, standardise more within the system like for ZPI for example and level the production (Heijunka).

In conclusion is the edge of knowledge is moved forward but to implement flexible concepts is more work and research concerning standardisation, multifunctional tools and how to be flexible in a global context needed. There are various views among departments in Skövde but Aurobay is present at multiple continents.

The automotive industry needs to be flexible to meet the demand of tomorrow.

Keywords: *Flexibility, machining, standardisation, system, and production concept.*

Acknowledgements

We would like to express our greatest gratitude to all the people who have helped and supported us during this BSc thesis work.

Firstly, a special thanks to our Chalmers supervisor and examiner, Peter Hammersberg, who has coached us with relevant questions and contributed with a positive spirit and attitude. Besides, he has followed our progress during the project by quickly responding to supervision meetings and with great interest of the topic.

We had also the advantage to have two highly regarded supervisors at Aurobay, Lars-Åke Andersson and Daniel Smedman. Both have helped us to answer questions or concerns in swift manner, as well as meeting us for regular discussions.

A special thanks to Erik Birgersson. He had the patience to assist, simulate the concepts and supply us with data relevant to analyse and base our recommendations on. We would like to sincerely say thanks to Stig Palmqvist, high school teacher in English and Swedish, who has taken his time to help out with language and improving the quality of the work.

During the duration of the work have we also been in contact with highly experienced people who have helped us to answer questions and improve our understanding of processes, products etc. Thanks to Christer Helander, Reine Thorstensson, Charles Prytz, Frida Söderlund, Anders Jonsson, Lars Johansson, Liselott Ullberg, Linda Almedal, Fredrik Green, Oskar Andersson Olin, Jenny Zell, Joakim Forsell, Jarent Arnholm, Anneli Wallgren, Jörgen Fock, Morgan Fredriksson, Johan Junefjäll and et al.

Our gratitude to Erik Grönlund, who helped us arrange the field visit to the Volvo Trucks Tuve plant, and to Robert Strand, Charlie Sand and Tania Werda for taking your time and answering our questions.

Finally, our profoundest gratitude to our families that have accommodate us in Skövde and Tidaholm making this work truly manageable and to Gunilla Andersson, grandmother of Ludwig, who has acted chauffeur to and from the train station in Skövde regardless of whether condition. Without their support had this not been possible.

Ludwig Almedal and Oscar Ivarsson

2023-06-04

Skövde

Abbreviation and keywords

Below is a summary of useful abbreviation and keywords that can be helpful for the understanding of this thesis work and its terminology.

Aurobay: The company name. Manufacture powertrain solutions.

Bedplate: A structure which together with the main block forms the cylinder block. “The bed to rest of an engine”.

Cam cover/Cam caps: part of the cylinder head and holds the camshaft in place.

CB: Cylinder Block, one of the manufactured objects in focus.

CH: Cylinder Head, one of the manufactured objects in focus.

Climate neutral: Achieving net zero greenhouse gas emissions. This can be done in three different scopes and by adding less or removing emission from the atmosphere.

CTQ: Critical to Quality.

Dedicated flow: A series of specialised/dedicated operations, generally capable of producing a smaller number of variants and products.

Discount rate: The interest rate used to determine the present value of future cash flow in a discounted cash flow analysis.

DMAIC: Is a five-step data driven improvement cycle consisting of Define, Measure, Analyse, Improve and Control.

DFA: design for assembly.

DFM: design for manufacturing.

Et.al.: Latin for *et alia* and means “and others”.

Etc.: Latin for *et cetera* and means “and other similar things” or “and so on”.

E.g.: Latin and stands for *exempli gratia* and means “for example”.

FIFO: First in first out.

Fishbone diagram: Can also be called Ishikawa diagram and cause-and-effect diagram. A tool to identify multiple causes to an effect or problem.

Flexibility: The ability to change or be changed easily according to the situation.

G1/Gen 1: Generation one engine

G3/Gen 3: Generation three engine

Gantry loader: An automated high speed workpiece transfer machine for loading/unloading unmanned operations.

Geely Holding: The concern name that Aurobay are a part of.

JPH: Jobs per hour

i.e.: Latin and abbreviation for *id est* and means “in other words/that is”.

Kinship chart: A chart outlining relationships like a family tree but often used in for more general context.

Machining: Removing of material and mostly milling in this project.

Main bearing. The bearing reduces friction of moving parts of machine elements to help movement in a desired way with minimum power loss.

MBS: Mass balancing system, an engine component, reduces engine vibrations.

Production concept: An abstract idea of production line.

Production variants: How many unique units can be produced.

Production volume: How many units are produced.

Pull flow: A production method that is only triggered by the actual demand of the customer.

Q.A: Quality assurance

RFID: Radio frequency Identification.

Scope: In sustainability contexts emissions are divided into different parts (scope), depending on how and where the emissions are emitted.

Simulation: A imitation of the operation of a real-world process or system over time.

Skövde: The city where the factory in this thesis work is located.

Standardisation: *Creating common conventions or ways of working so that it works smoothly with other parts.*

System thinking: A way of making sense of the complexity of the world by looking at it in terms of wholes and relationships rather than by splitting it down into parts.

Takt time/takt: A German manufacturing term to describe the required product assembly duration needed to match the demand.

VEA: Volvo Engine architecture, the current engine family in production. In line 4-cylinder engine first introduced in 2013.

VEP: Volvo Engine Petrol

VED: Volvo Engine Diesel

VSM: Value stream map

Volvo Tuve: A truck factory in the urban area Tuve, Gothenburg.

WIP: Work in process.

UN global goals: 17 goals set by United Nations and its member countries for peace and prosperity for people and planet, now and into the future.

ZPI: Zero-point index, a standardised fixture system implemented by Aurobay to handle more variants in the same machine and save set up time.

1. Project introduction and definition

In this chapter is the project introduction and the deliverables, scope and limitations are discussed and presented.

1.1 What is Aurobay?

Aurobay has a profound and long history prior to becoming a stand-alone company within the Geely Holding. The introduction “*What is Aurobay?*” provides a brief but comprehensive background to the company.

AB Volvo has been present in Skövde since the founding of the company with production of both heavy-duty engines for Volvo trucks, buses, construction equipment and other demanding applications, as well as powertrains for Volvo Cars. The production in Skövde started in 1907 with the manufacturing of the marine engine *Penta B1* at Skövde Gjuteri & Mekaniska Verkstad (AB Volvo, 2023). However, Skövde Gjuteri & Mekaniska Verkstad had been in business since 1868 and its founder John G Grönvall played a vital role in the start of the production of the B1 engine. The name “Penta” originates from the Greek word *penta*, which means *five* and represents the five men who contributed to the launch and success of the engine. The production grew during the following decade and in 1919 the name changed to *AB Pentaverken* (Nationalencyklopedin, 2023).

Gustav Larsson together with Assar Gabrielsson, the later born in Korsberga in the outskirts of Skövde, founded Volvo in 1927 but research- and development work had been carried out prior to the launch of the first vehicle. Larsson and Gabrielsson made an initial order for a Penta manufactured engine in 1925 and more orders were received during 1926 and 1927. As Volvo production kept on increasing throughout the late 1920s, the number of Volvo engines exceeded the number of Penta engines and Volvo business became progressively more important for Penta. Volvo bought Penta in 1935 and engines were from now on produced at *Volvo Pentaverken* (AB Volvo, 2023).

For an extended period of time all activities related to engine manufacturing, i.e., foundry, machining and assembly of both heavy-duty and car engines, executed at the same plant. However, during the 1980s did the long-term production forecast indicate a change in the demand for cars manufactured by Volvo. The forecast indicated the need for a new car portfolio produced in much greater volumes than earlier and with more efficient engines concerning emissions and fuel consumption. Thus, Volvo engine engineers developed a completely new modular engine family, *Volvo Modular Engine*, consisting of 4-, 5- and 6-cylinder variants (Bergström, Bengtsson, Larsson, Denbratt, & Petersson, 1991). Additionally, existing production facilities identified by engineers to lack the required capacity in order to meet the demand and the need to build a completely new engine plant soon became inevitable (Ljungqvist, Varför en ny motorfabrik i Skövde i början av 1990-talet?, 2002).



Figure 1: the inline 5-cylinder petrol engine, part of the new engine line-up from Volvo (Volvo Car Group, Corporate Communications, 2013).

On the 18th of September in 1985, at an AB Volvo board meeting, the final decision for a new engine plant in Skövde was taken. The project was granted an initial investment of 200 million Swedish crowns and an additional billion was added in 1987 and the project was by then the largest investment in the history of Volvo (Ljungvist, Beslut om ny fabrik, 2002). The factory was finalised in steps and first out was the H-factory in 1988 with the machining of cam shafts. Machining facilities for crank shafts, cylinder- heads and blocks were finished during the period 1988 to 1991. Likewise, during the same period assembly lines installations were finished. Production had started in a limited scale 1988, but under great secrecy since the articles produced were part of the Volvo 850 project.

Volvo stated that the 850-project presented four “world-beating breakthroughs” new attributes consisting of a Delta-link rear axle, *Side Impact Protection System (SIPOC)*, self-adjusting front seat belt and the transverse inline 5-cylinder engine which the Skövde plant played an important role to make real (Volvo Car Group, Corporate Communications, 2013).



Figure 2: the Volvo 850, here as an estate, became a great commercial success for Volvo in both Sweden and abroad (Volvo Car Group, Corporate Communications, 2013).

In June in 1991 Volvo showed the new 850 car to the public and the secrecy was lifted. Six years after the first decision was made, was inaugurated the factory on the 30 of September 1991 and production ramped up to meet the increasing demand. The total cost for the factory landed at five billion Swedish crowns (Ljungvist, Projekt G2 offentliggörs, Invigning av Östra fabriken, 2002).

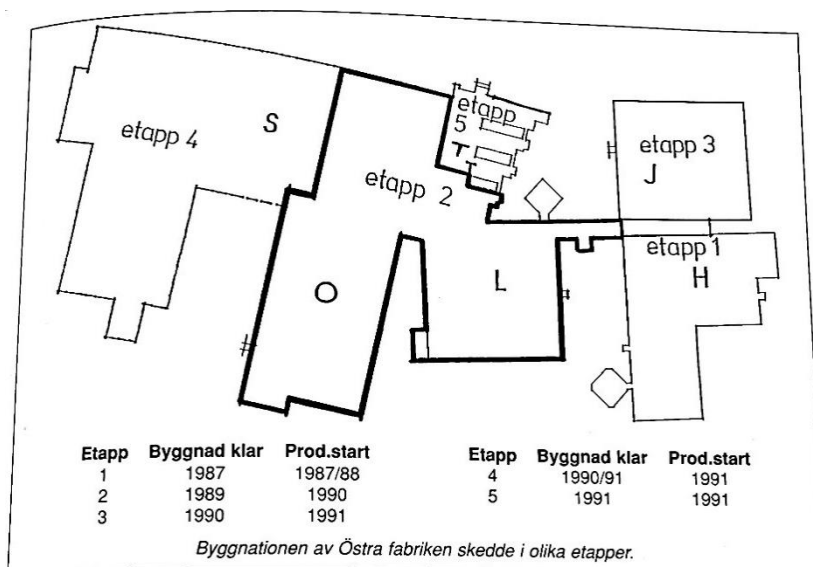


Figure 3: an overview of the plant (Ljungvist, Beslut om ny fabrik, 2002).

Volvo kept on launching new car models with the introduction of the S/V40 and C70 in 1995 and 1997 respectively, as well as the new car platform P23 in 1998. All could be ordered with high-end petrol engines from Skövde. Yet, diesel engines were offered but production and

development were outsourced to the Volkswagen group. However, in the middle of the 1990s car manufactures experienced an increase in European demand for diesel engines since they offered lower fuel consumption and in addition was the new emission regulation, Euro III, set to be introduced in 2000 which the Volkswagen diesels not fulfilled. The request from Volvo to further develop the diesel was denied and in 1997 Volvo therefore had to develop and manufacture its own diesel engine. The ballot to produce it fell on Skövde and when it was introduced to the public, at the year 2000 Paris Motor Show, more than 40 000 hours and an additional 3 million kilometres on road had been spent on testing. The Skövde plant managed to deliver the required production capacity on time with both the installation of new assembly- and machining lines. The production started in August 2001 (Ljungqvist, Dieselmotorer; Produktlansering, 2002). During the same time period Volvo Car Cooperation was acquired by Ford Motor Company for 50 billion Swedish crowns and was the result of the global trend, where automotive companies were consolidated (Ljungqvist, Volvo Personvagnar - en del av Ford, 2002)

In 2008 the world economy was hit by the most extensive financial crisis since the Great depression in the 1930s with increased unemployment, falling stocks and banks ending up bankrupt (Andersson F. , 2023). Sweden and Volvo Cars were not spared. Volvo Cars reported 2008 to be tough year with global sale volume plummeting by 18.3 % and over 4600 employees had to be laid off. Despite the economic turmoil the XC60 SUV was launched, and the company introduced an aggressive emission reduction plan. The plan included enhanced powertrain technologies and completely new engines such as the *DriveE* concept (Volvo Car Group, Corporate Communications, 2009). Skövde became a natural part of the plan and guaranteed the survival of the plant through the crisis. In 2010, just after 10 years part of Ford, was Volvo Car Cooperation sold to the Chinese car manufacturer *Geely Holding* and the Volvo plant (Helmersson & Westholm, 2023).

Over 20 years after the launch of Volvo Modular Engine (VME) was the *Volvo Engine Architecture (VEA)* engine family introduced in 2013. In resemblance with the VME, totally made in aluminum and offering a wide range of torque and power outputs, despite only being offered as in-line four cylinder and with a displacement of just 2.0-liters. The reasons behind the launch were to create a common architecture that paves the way for lower emissions, enhanced efficiency and hybrids solutions (Bickerstaffe, 2014).

In recent years has the plant managed to deal with a swift increase in demand since the launch of the all-new vehicle platform, SPA, in 2014 which paved the way for a new line up of cars. An important milestone was reached in 2018 when the 10th million manufactured engine left the plant (Eriksson, 2018). In the beginning of the 2020s Volvo ruled out an ambition of only retailing pure electric vehicles by 2030 and as consequence was the decision made to start joint venture with Geely focusing of developing the next generation powertrains. Thus, Aurobay was born (Volvo Cars Media Relations, 2021).

What is Aurobay then? Aurobay is a company that focus on developing the powertrains of the future and the plant in Skövde will be a key actor. It is not the first time Skövde is being stand-alone from Volvo but however, the plant has been an enabler of the commercial success Volvo has experienced over the years. Consequently, Aurobay has a profound history of manufacturing and undertaking challenges reaching back over 100 years.

A footprint on two continents



Headquarters

Gothenburg, Sweden
R&D, Digital, Corporate functions



Skövde plant

Sweden
Manufacturing Engineering, Assembly,
Production
VEP4, VED4



Zhangjiakou plant

China
Manufacturing Engineering, Assembly, Production
VEP4, GEP3, MEP1, MEP2, Geely CH/CB/CS

Internal

Figure 4: A map illustrating Aurobay's production facilities and headquarter. Photo used with permission from Aurobay

1.2 Sustainability at Aurobay

Aurobay, earlier Volvo Car Engine, has a long history of sustainability reaching back to 1945 (Volvo Car Cooperation, 2023). Following the timeline of sustainability, everything starts 1945 with fixing broken car parts and 1972 their first environment declaration was written. In 1976 they develop the three-way catalysator that reduces 90% of toxic gas from their cars and in 2012 did they produced the world's first diesel hybrid car.

At the factory in Skövde of which this thesis work is written the whole plant got classified as climate-neutral in 2018. This through refine engines with electricity from renewable sources and all heating from biomass, waste incineration, and biofuels. Production wastes are also sorted out and sold to other industries, pallets are replaced with recycled packaging material and waste aluminum is sent to their local supplier. To get a deeper understanding of climate-neutral and the journey there but also the way towards net zero an interview with Aurobay's energy optimizer Johan Junefjäll was conducted (Junefjäll, 2023).

To describe climate neutrality Junefjäll explained that the emissions can be divided into three scopes. Scope 1 includes direct emissions from the company's facilities and company's vehicles. Scope 2 includes purchased energy, steam, cooling, and heating for their own use. Through long and hard work as well as good collaboration with the local heating plant they have used renewable energy for more than 15 years. It is in scope 2 there are climate neutral. The refining of their products to their customer and how this corresponds to climate neutrality and responsibility for the other emission in scope 1 and scope 3 could Junefjäll not answer but gave us some contact information. Further on the scope 3 are the indirect emissions and can be divided into upstream emissions that are before production and downstream emission that are after production. For all scopes and more details see figure 5.

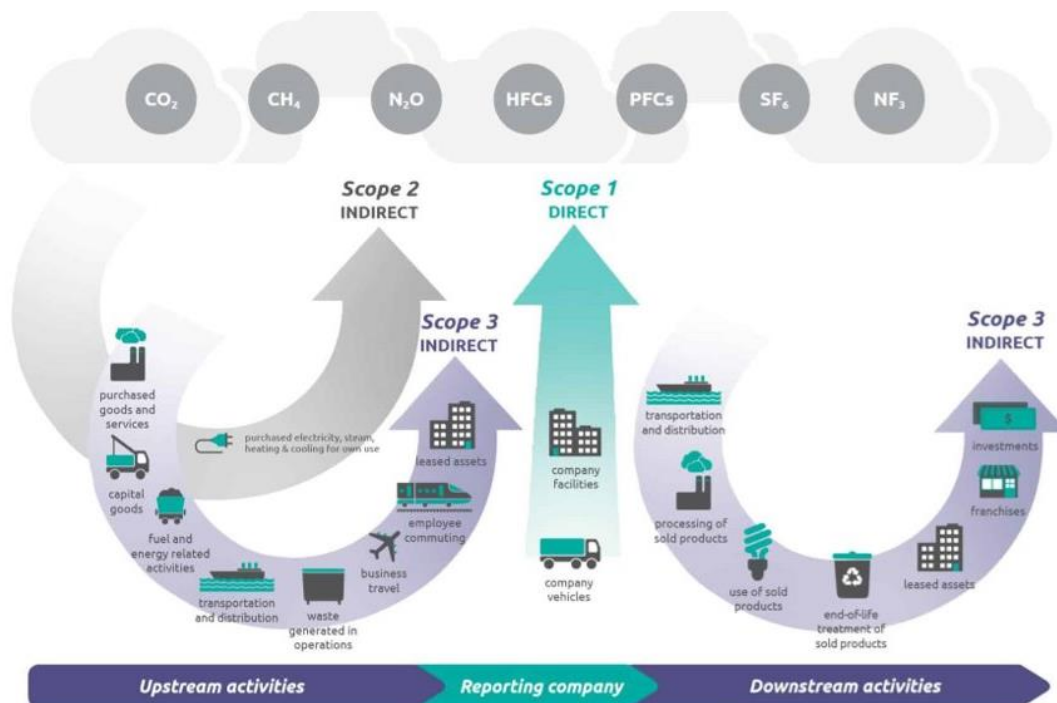


Figure 5: Scope 1,2 and 3. Direct and indirect emissions from Aurobay. Photo used with permission from Aurobay

After the scopes Junefjäll showed Aurobay's long-term ambitions and how they relate sustainability for them and their *purpose*, *strategy* and *focus areas*. First there is a straightforward purpose. Net-zero by 2040 of greenhouse gases emission (see figure 6).

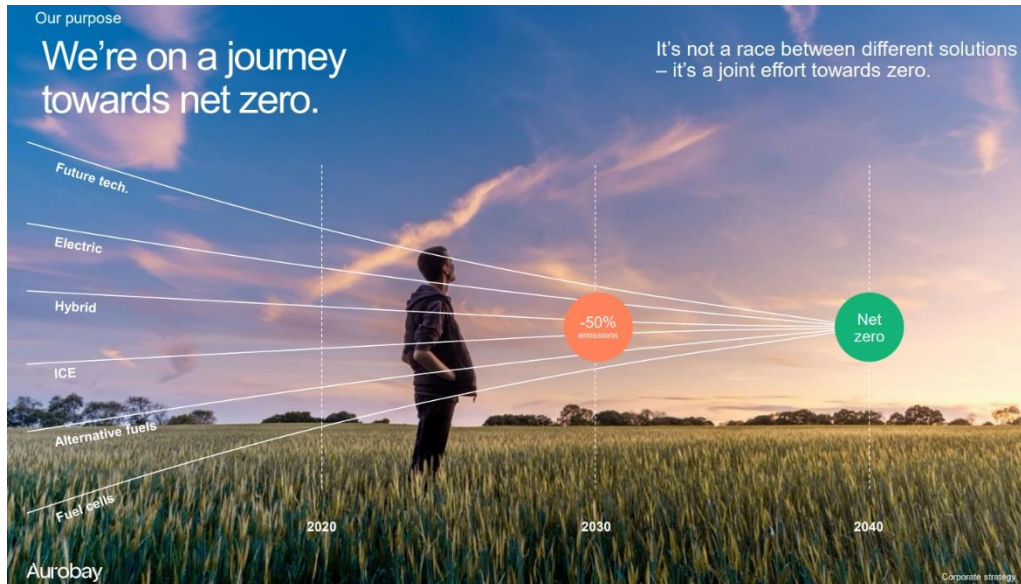


Figure 6: It is not through one solution; it is joint effort according to Aurobay purpose net zero can be reach. Photo used with permission from Aurobay.

Net zero means greenhouses are okay but if they add, they need to remove the same amount in the atmosphere according to Junefjäll. Aurobay believe that Electric cars is not a silver bullet solution within the car industry and that a joint effort of future tech, electric, hybrid, ICE (internal combustion engine), alternative fuels and fuel cells are the solution. For example, they have investigated an investment of HVO100 (100% Hydrotreated Vegetable Oil) that was at that moment not much more expensive but there was palm oil in it. The price took off and the savings of CO2 would be small. Palm oil will also be forbidden in the process. Another solution than electric cars Junefjäll can see big potential in is the diesel hybrid market. This is because a diesel engine has a big tolerance and works with lots of different liquids. At Aurobay they have manufactured a zero-emission engine and several projects are in progress for facing the demand of tomorrow. Flexible production he sees as one brick in the building of a sustainable future when things changing fast. A flexible line is also a good way to not use electricity and material that is not required.

Junefjäll also showed a graph of the recycling rate of energy is above 50% and how the energy consumption has been an important question and a long journey. See more about the journey of energy recycling in figure 7.

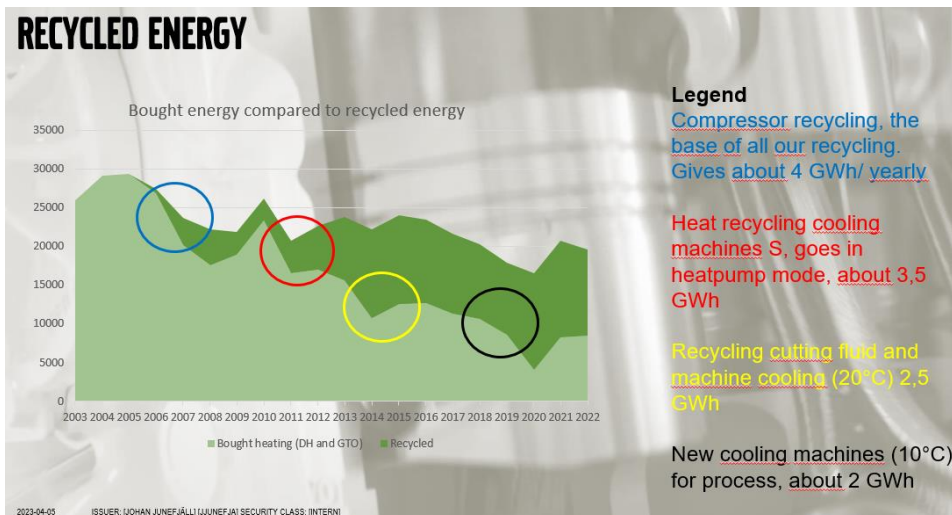
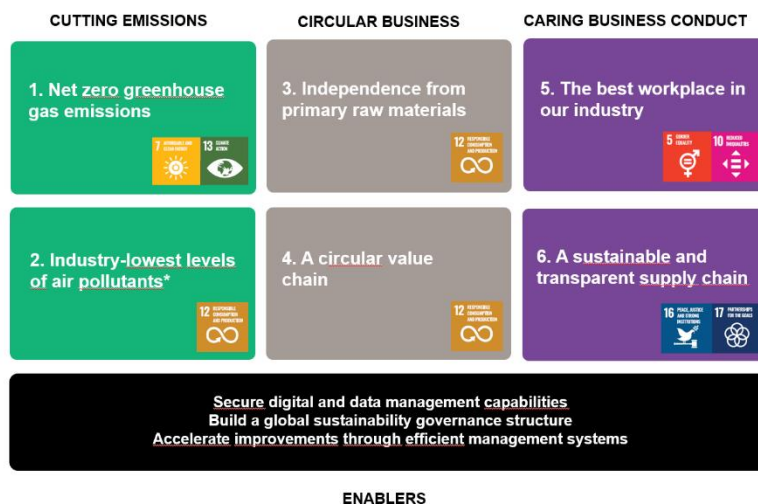


Figure 7: Recycled energy at Aurobay since 2003 until 2022 with four main events decreasing there bought energy. Used with permission from Aurobay.

Thereafter they are a part of UN global goals and Aurobay aimed to put “sustainability and quality par to each other” through an internal prize for CO2 emissions. Moreover, they also aim to be the best workplace in their industry, a circular value chain and industry-lowest levels of air pollutants (see figure 8 for sustainable strategic). In this thesis work UN goal number 12 “sustainable consumption and production” is the most central (Förenta nationerna, 2022). To follow the framework of sustainable consumption and production when develop concepts further on. This can be made by energy efficient machines and good sleep modes in the flexible lines.

Our sustainability strategic focus areas



Aurobay *Here we refer to harmful air pollutants from combustion technology, such as NOx, HCs, CO and particulate matter. Greenhouse gas emissions are excluded from this focus area

Figure 8: The focus areas at Aurobay and which field of sustainability they are connected to. Used with permission from Aurobay.

1.3 Defining the project scope

The project team was handed a project description containing goals and deliverables as well as a brief background to *why* the project was initiated. However, the project description does not entirely define the problem or describe the voice of the customer and key parameters of value for the company might be lost if not defined correctly. The define phase will present a breakdown of the assigned task, identification of important project deliveries, the specific problem, and goals. Besides, project scope regarding what and what is not included are set by the project limitations.

1.3.1 Framing and understanding the situation of today

On the first day of the project was an introduction given by the team's Aurobay supervisor Lars-Åke Andersson. The team had been handed an initial project description prior to the introduction, which included a problem formulation, purpose, and goals for the project. Andersson gave a brief, but thorough, background on how the machining processes has developed over the years and took the team on a Gemba walk to the cylinder head production. When production started back in yearly autumn 1991 were machining operation mainly executed in high volume machining lines, with rigid transfer machines capable of processing parts for both four, five- and six-cylinder petrol engines but however was the utilisation of equipment rather low since if e.g., a set of four cylinders was machined were tools, fixtures etc., required for the five and sixes not utilised at all.

As production figures altered and as new and old products were added or removed from the product portfolio was the concept with the rigid transfer lines dropped and manufacturing engineers turned to machining centres which have the ability to perform a wide range of machining operations. The machining centre offers better equipment utilisation since tools and fixtures can be used for more variants. Another transition was also made in the same time period there machining operations of different variants of cylinder heads- and block were divided into individually flows, instead of producing all variants (four, five, six-cylinder, diesel, petrol etc.) in the same line. Yet, the demand remained high and therefore was high capacity regarded as important aspect when designing and investing in new production lines, with designed capacity often reaching 250 to 350 thousand in yearly volume.

As of today, is the machining operations divided into seven departments responsible for different parts of the engine (see table 1) and production capacity varying between the departments. The engine manufactured today is the *Volvo Engine Architecture* platform (see *What is Aurobay*) and currently is both generation two and three of the petrol and diesel variants in production.

The demand has in recent time become lower than the designed capacity, i.e., the degree of equipment utilisation is not optimal, and low volume production is not suitable in the already

existing production facilities. Nevertheless, an increase in demand for existing products is a possibility and therefore is the need for additional low volume facilities with ability to new customer demand a reality.

Table 1: the machining departments at Aurobay.

Machining departments		
Department	Part	# flows
O - factory	Cylinder heads	3
L - factory	Cylinder blocks	1
J - factory	Cylinder blocks	2
J flex - factory	Crankshafts	1
H - factory	Camshafts	1
H - factory	Crankshafts	1

However, a change in demand has arisen where requirements and expectations for a greater variety of variants and products as well as fluctuating production volume have become more important parameters than before. Lately, has uncertainties regarding the future of the internal combustion engine been discussed frequently with the European Parliament voting of banning CO₂-emitting technology in the transport sector from 2035 and hence jeopardising the internal combustion engine. A last-minute intervention from Germany, who said it would veto the bill in the European Council, paved the way for using climate neutral E-fuels in internal combustion engines even after 2035 (Abnett, 2023). Yet, there are more imminent challenges for the industry like the upcoming *Euro Seven* legislation that most likely will be law in 2025 for passenger cars and 2027 for trucks and other heavy-duty applications. The legislation is imposing stricter and tighter levels of tailpipe emissions, e.g., carbon dioxide and nitrogen oxides, as well as for the first time regulating the emitted particles from the braking system with levels down 13 % and 27 % respectively from the previous emission bill, the *Euro Six*. Experts within the field determines it is feasible for the automotive industry, but it will however be a great challenge (Kristensson, Euro 7 inte den död för förbränningsmotorn som vissa befarat, 2022).

Nevertheless, the innovation and research in order to enhance the internal combustion engine technology is ongoing with new innovations like low-friction coatings, advance turbocharging or water injection and is discussed in the article *It's too soon to say goodbye to internal combustion* (Schnurrer, Schiel, Wyman, & Rengarajan, 2022). Recent calculations highlight that investing in the latest developments and innovations could save 1,8 tons of CO₂ per C-segment car in a ten-year period and a broad implementation just Europe could imply a 60-million-ton reduction of CO₂ emissions. The author of the article states the car makers should embrace strategies concerning the development of internal combustion in order to make the reduction viable and not run away from the technology. Additionally, the development of renewable and climate neutral fuels have already come along way, in particular biodiesel there the Finish petroleum company *Neste* is avantgarde with a yearly production of 4,5 million tons of biodiesel offering potential synergy together with the latest innovations (Kristensson, Blir skogens rester framtidens fordonsbränsle, 2022),

Thus, the automotive industry has plenty of new technologies at their disposal and inquiries from customers to produce them could soon become a reality soon meaning that manufactures most have the flexibility of meeting the demand. As of today, at Aurobay, is the time from the production investment decision to start of production (SOP) at least one and a half year meaning new inquiries from customers will more than that time and hence, the risk of losing key customers and contracts have become a potential reality. Consequently, Aurobay is required to investigate new approaches on how to be flexible and deal with the imminent changes in demand and inquiries.

1.3.2 Understanding the voice of the customer

The team identified both internal and external customer determined. Internal and external customers should respectively be described as people within the manufacturing (ME)- and production engineering (PE) departments, such as Andersson, as well as the assembly and machining departments and Aurobay as a company. The external customers were Chalmers. Moreover, decisions on the primary data collection method and made a table to visualise it (see table 2).

Table 2: the project main customers and how the team should collect the initial information.

Project customers			
External	How to collect info?	Internal	How to collect info?
Chalmers	Baseline reasearch	ME dep	Interviews, Gemba
Researcher within the field	Baseline reasearch	PE dep	Interviews, Gemba
		Maching dep	Interviews, Gemba
		Assembly dep	Interviews, Gemba
		Aurobay as a whole	Interviews, Gemba

The team quickly recognised that the customers had varying expectations and needs concerning the project outcome, but their main deliverables could be identified by discussing the project description, going to the Gemba and meet the identified customers. Hence, the team summarised the identified deliverables, expectations, needs and concerns regarding the outcome (see table 3).

Table 3: the VOC for the project.

Voice of the Customer		
Customer	Deliverable/issue	Needs/expectations
Maching dep	New productions concepts and challenge the thinking of today concerning how machining is done	New ideas for production concepts and access to the report and definition of flexibility
Assembly dep	Bring knowledge that might be applied to at assembly operations	A defintion on flexibility and access to the findings and report
Aurobay as a whole	Add new information and approaches on how to handle low volume machining inquiries	Presentation of outcome and access to report
Chalmers	Planning and final report, as well as project presentation	Thesis work within the framework set by Chalmers
Researcher within the field	New knowledge	Final report
ME dep	New approaches on how to tackle low volume production in machining and analyse potential concepts and their benifits	Comparative analysis focusing on planning conditions, tool set-up, fixtures, investments, costs and profits. The concepts will have following attributes: Volume: 10 k and 30 k Comperative analyse between 3 lines à 10 k dedicated to one product and and 1 line at 30 k with flexibility of three products (CH, CB & BB). Final report and presentation.
PE dep	New approaches on how to tackle low volume production in machining and be given analysed concepts who is flexible and with a year volume of 10k to 30k.	Final report and presentation

The key outlines from the VOC are:

- Move the limit of knowledge on low volume production.
- Move the limit of knowledge concerning flexibility.
- Comparative analysis highlighting positive features and drawbacks for each concept.
- Being flexible or having flexibility in machining.
- New thinking and approaches.

1.3.3 Benefit assessment

When performing a DMAIC project will the *project benefit assessment* help to determine the value of the project and then in time the benefits will show. The benefits identified in the define phase should be used as an input when analysing the proposed solutions in the improve compared to the cost against benefits. Moreover, could normally benefits be categorised into *hard* respectively *soft* benefits, i.e., benefits directly measurable in financial value and those benefits not immediately noticeable in monetary values but are however valuable for the company. After mapping the projects voice of the customer could several projects' benefits be identified (see table 4).

Table 4: the project benefits.

Project benefits	
Hard	Soft
Machined cylinder heads- and blocks and bearing brackets	Flexibility understanding
Improved ability to meet customer inquiries	Mapping of products, variants and processes
Increased equipment utilisation	Low machining concepts with comparative analysis

1.3.4 Understanding the project scope and boundaries with effective scoping

The effective scoping is a reworked version of SIPOC (*Supplier, Inputs, Process, Outputs, Customer*) and provides a helicopter overview of the process and helps to determine the elements in the project scope (see figure 9). The method is developed by Peter Hammersberg and is described in the methodology chapter.

Process owner (org): Aurobay		Project sponsor:		Project team: Ludwig Almedal and Oscar Ivarsson		
<p>Effective Scoping of continuous improvement projects SIPOC 2.0</p> <p><i>The <u>sequence in itself</u>, of questions Q1-Q4, Q5-Q7 and Q8-Q9 below, is key to facilitate consensus in the shift of an organisation's mindsets from push to pull, in accordance with the principles of Lean Six Sigma</i></p>						
Supplier	Input		Process	Output		Customer
8b. Who supplies the inputs?	Q8a. What are the inputs to the system?	Q9. What does the system require of the inputs?	Q7a. Team/project jurisdiction of changes	Q1. What comes out (of the physical flow) - OUTPUT?	Q3. What is required of the output from this particular user (List of big Y's and improvement proposals)	Q2. Who uses the output?
Aurobay Aurobay and Chalmers Aurobay and Chalmers Aurobay Chalmers Library, course literature Aurobay	Thesis work inquiry Supervisors Network of competent people regarding methods, process etc In-house investigations Earlier research about production philosophies, flexibility etc. Going to gemba	The information needs to up to date and has a scientific ground.	Propose suggestions and new way of thinking concerning machining production. Not purchase machines or other products and no execution of suggestions such as implementation of production methods. Q7b. What competences are needed in the team (WHO)? Fresh mind of doing things. The team competence required is production engineering, machining knowledge etc.	New information is coming out constructed like a report about new flexible concepts for machining. New information to inspire, give ideas and perspective on how to meet the need of tomorrow. Not to take any directly action and implement. (From the physical flow that the report describes CB, CH and BB will come out).	1. The concept is more flexible but still have the ability to produce CB, CH and BB for a reasonable cost. 2. It is easy to understand the report so the report do not disappear in any noise. 3. The concept is not created by Aurobay in other words the insights are new. 4. Is delivered in time. 5. The report moves the limits of knowledge and complies with Chalmers standards. It is a thesis work not a consultant project. Q4. What specific metrics can be used to characterise the aspect(s) from the list of big Y's that you are addressing in this specific project? Can you be more specific? Not yet developed metrics for flexibility but a quality measuring and a concept answering yes to some flexibility questions. Before any metrics can be developed flexibility need to be defined. Kappa analyzes will be used for developing the definition and as well answer how metrics should be formed. Set up time will be a metric, complying with qualitative judgements. Q5. What is the baseline of the y and can that precis y be measured today (and can old data be trusted)? In other words: What is the facts behind the problem that form the base for our improvement promise? Show the data/proof of a problem! Facts: Petrol and diesel demand is changing, Aurobay will presumably receive new inquiries from customers and need a new way of thinking concerning machining flow. There is lack of data related to flexibility but investment data is possible to find. The baseline is 4 lines for all variants of CH. 3 lines for CB and no production for BB. Q6. What other Y can not be lost in the process (constraints)? Time cannot be lost, input/contact with customers and cost (quality and technical) will be applied in next step).	Primary Lars-Åke at Aurobay will use this for new insights from someone outside the box. Lars Åke is supervisor and he gets information during the whole process. The context is to create new concepts and rebuild/build new manufacturing lines for meeting a demand that is changing more quickly. The end customer is car buyers and they want to have more flexibility in choosing a new car for a reasonable prize. The machining departments are also potential customers of the output. Aurobay as a whole will benefit from the output since new information and inputs creates competitive advantages.
			Name of the flow to be improved:			
			Thesis work- Aurobay			
			From where is the physical output shipped?			
			N/A			

Figure 9: the effective scoping for the project.

2. Theory

In the theory chapter answers, “*what do the world know of the problem today?*” and what requires further scrutiny and research.


2.1 The term flexibility

The term *flexibility* is universal and as a wide spectrum of application. The “average Joe” will most probably encounter *flexibility* in their everyday life. If someone or something is *flexible*, is it likely to be described to have adaptability, changeability, or versatility (Svenska Akademien, 2022). E.g., airlines and airline ticket agencies advertise *flexible tickets* (Travel Perk, 2023) to have a greater changeability and versatility since they offer refund in the event of cancellation or the possibility to change the departure if the travellers planning have gone south, and all this without an extra fee. Another example is SJ, the Swedish State Railways (*Statens Järnvägar*), who offers tickets with a varying degree of flexibility (see figure 10).

Customise journey

Departure [Change](#)

Göteborg C–Skövde C
21 March 08:24-09:25
1 adult


SJ High-speed train, X 2000, Train 425

[Travel details](#)

1 class [Change](#) ▼

Flexibility

<input type="radio"/> Non-rebookable	295 SEK
<input type="radio"/> Rebookable	395 SEK
<input type="radio"/> Refundable	485 SEK

[Our flexibilities](#)

+ Select seat

Figure 10: SJ normally provides three different kinds of flexibility levels. Picture retrieved from SJ AB (SJ AB, 2023).

During the 1960s and 1970s as market demand started to change was also the need for customisation of products and services recognised in the industry. Delivery at customer demand was also recognised and becoming *flexible* was the winning strategy in order to meet and cope with fluctuating demand and increasing customisation. The industry therefore invented *Flexible Manufacturing System*, FMS, which is defined as a process capable of manufacturing and processing a variety of diverse parts concurrently and production volume follows the customer demand (Shivanand, 2006).

Additionally have flexible engine families been common practices at Volvo Cars since at least the introduction of the *Volvo Modular Engine*, consisting of inline four-, five- and six-cylinder petrol variants. By extensively using identical components and articles, and machining major components such as cylinder heads, cylinder block etc in common transfer lines, increases production efficiency and keeps costs down (Bergström, Bengtsson, Larsson, Denbratt, & Petersson, 1991). More recently, *Volvo Engine Architecture (VEA)*, offers similar flexibility to Volvo and Aurobay.

Hence, the term *flexibility* is applied in both everyday situations and services, but also in industry and technology. The broadness and extent of term implies further investigation and definition of *flexibility* in the project.

2.2 Literature studies

In the literature studies chapter is “*what is known today?*” within the field of research presented. Two studies concerning industry flexibility and production philosophies were studied in order to give the team a background and context on what knowledge exists today.

2.2.1 Flexibility

In the following section is the literature identified as relevant for flexibility presented and highlighted.

2.2.1.1 Lean Flexibility

Lean flexibility a thesis work at Chalmers institution of production Engineering by Peter Almström and Sandro Vecchiattini.

For a deeper understanding of flexibility, the team studied the thesis work *Lean flexibility* by Almström and Vecchiattini. The thesis work was executed at Ericsson Microwave Systems AB with the purpose to research the need of flexibility and potential actions that can be taken to increase flexibility in a Lean way (Almström & Vecchiattini, 1996). In their work they have created a model of flexibility at a system level and factors around. It is divided into various terms such as resource flexibility, function flexibility and external uncertainty that affects flexibility. Then these terms are affected by several other factors. Figure 11 below gives a better insight:

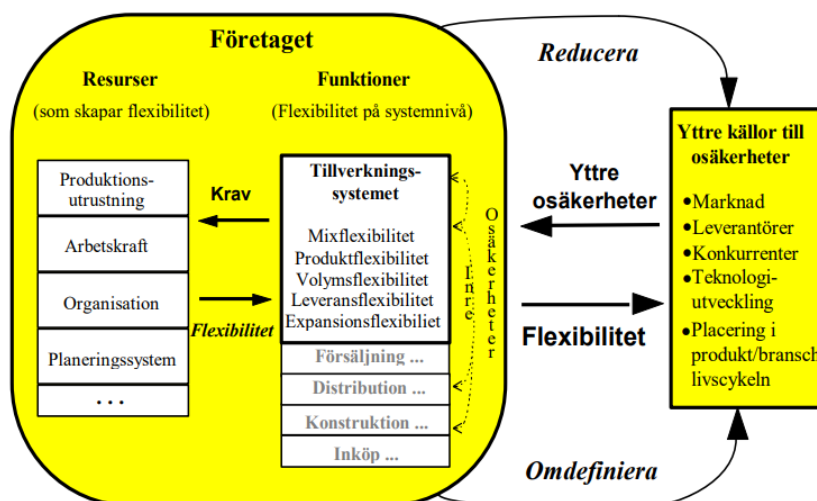


Figure 11: A holistic picture of resource flexibility, functional flexibility and external sources of uncertainty (Almström & Vecchiattini, 1996). Used with explicit permission from Peter Almström.

As discussed earlier, the term flexibility has a broad area of application and could help to define flexibility.

Their definitions are as follows:

- *Mix flexibility*: The ability to reschedule production within a predetermined set.
- *Volume flexibility*: The ability to handle fluctuations of the aggregate the production volume within a predetermined range, without making any larger investments.

- *Product flexibility*: The ability to phase in products which the manufacturing system contains partially new or completely new constructions.
- *Deliver flexibility*: The ability to, on selected occasions, reduce the time between incomes customer order and delivery.
- *Expansion flexibility*: The ability to increase the capacity of the manufacturing system, if necessary, through expansion in a resource-efficient way.

After these terms are defined, next step is to measure and the authors states that flexibility from a strategic point of view must be measured relatively to the flexibility of competitors to have a meaningful comparison. Absolute measures are not sufficient if it is not clear what a certain amount of flexibility means for the company's competitiveness. Instead, it is better to indicate directions for how flexibility should be developed and set interim goals to strive towards these. Measuring flexibility is usually focused on measuring it at a low level, for example at the machine level. It is not possible to measure flexibility based solely on objective data from the system, and most data must be derived from the managers' subjective assessment of system flexibility. An alternative way to measure flexibility is to do so in economic terms by measuring the difference between expected earnings with and without flexibility. Another method suggests that flexibility should be measured as the cost of change related to how likely the change is to occur or “*penalty to Change*” (POC).

$$POC = \text{Probability of change} \times \text{the cost of the change}$$

The method was first proposed by George Chryssolouris who tried to find a suitable way for measuring flexibility. POC measures the cost of a change relatively to the probability that the change will occur. The higher the POC, the less flexible the system. By comparing the POC values for different options, you can choose the most flexible option when, for example, purchasing a new machine line. However, it is important to note that conducting a full investigation of all costs and probabilities of events occurring can be very time-consuming and laborious.

Lastly flexibility is one of the elements for productive companies in the strategy of production together with quality, time and cost. Depending on the strategy and the uncertainty, flexibility is essential. At Ericsson Microwave they saw mixed flexibility could be improved by more knowledge to the operators and more lean set-up time at surface mounting.

Strategi	Angreppssätt	Innebörd för flexibilitet
Anpassning	Defensiv	Kräver flexibilitet
Reducering	Proaktiv	Reducerar behovet av flexibilitet
Omdefiniering	Proaktiv	Kräver flexibilitet

Figure 12: Strategy, approach and meaning for flexibility (Almström & Vecchiattini, 1996).

To summarise the report, flexibility is a broad term that in a production company can be divided into resources, function and external uncertainty factors. Within functional there is mix, volume, product, deliver and expansion flexibility and these are easier measured in comparison to other for understanding the grade of flexibility. “*Penalty of Change*”, POC, is

one way of measure flexibility, but a full investigation can be time and cost consuming. At last, depending on current strategy flexibility is essential.

2.2.1.2 Towards increasing operational flexibility in final assembly using industry 4.0 enabling technologies

Moreover, Omkar Salunkhe licentiate thesis work *Towards Increasing Operational Flexibility in Final Assembly using Industry 4.0 Enabling Technologies* (Salunkhe, Towards Increasing Operational Flexibility in Final Assembly using Industry 4.0 Enabling Technologies , 2021) was studied and Salunkhe had developed two research questions. Both concerned how operational flexibility may be increased in final assembly by using industry 4.0 technologies and collaborative robots. According to Salunkhe's findings *operational flexibility* (also referred as *flexibility of manufacturing operations*) defined to a manufacturing systems ability to respond to unexpected events and disruptions caused by non-planned activities. The definition can be divided into the context of *part or product* and *process*, where a product can be produced in more than one way by applying different methods and machines as well as a production system's ability of producing a given part in altering machines and ability to provide the correct material to produce the desired amount. Hence, a product capable of being refined regardless of the machine and process type at hand is an example of a process with operational flexibility.

Driving factors of operational flexibility are also identified and discussed. Five uncertainties are highlighted as the primary drivers and are reasons for being flexible. They are as follows:

- I. *Environmental*. A production system is required to adapt and have the ability to deal with events beyond the company's control such as war or natural disasters.
- II. *Manufacturing*. Unpredicted disturbances in the process, e.g., machines breaking down, material shortages etc., need to be responded to accordingly. Changes in product design and materials are likewise included.
- III. *Technology*. Enhancement and refinements of existing products as well as launch of new made by R&D departments requires swiftly adoption by production.
- IV. *Customer requirements*. System ability to adapt to Customer demand, preferences etc (Salunkhe, Operational flexibility, 2021).

Production systems having shortcomings with uncertainties are likely to have flawed flexibility. Moreover, sources of operational flexibility are reviewed in the thesis work and five areas related to production system are identified. The sources are:

- I. *Production system infrastructure*. Everything from systems design, workstation and production schedule.
- II. *Machines and equipment*. Set-up time, tools, reconfigurability of machines and ability to manufacture a wide range of product.
- III. *Operator training and skills*. An operator or an assembler's competence to manufacture products according to the defined quality standards and how well they can start working on new products or variants due to changes in the process.

- IV. *Assembly instructions.* Personnel working in a production environment needs to have adequate instructions and methods on how to execute tasks. Well defined and agreed-upon instructions is an enabler.
- V. *Materials and logistics.* Delivery of material in time, at the right quantity and right quality is vital for operational flexibility (Salunkhe, Operational flexibility, 2021).

Despite the thesis work main focus was final assembly it entailed useful information concerning flexibility which can be applied in the project. To summarise a definition of operational flexibility mapped and defined in Salunkhe licentiate thesis work and both factors causing the need for flexibility and source for operational flexibility is discussed. The driving factors and sources highlight that the total system design, e.g., continuous flow, job shop and more, capability of manufacturing a broad range of products in varying volume and well skilled operators leaning on standards and standardised organisation are important factors for succeeding with flexibility.

2.2.2 Production philosophies

In the field of manufacturing and operations management, production philosophies play a fundamental role in guiding organisations and set the frameworks for shaping their way to approach production systems and new concepts. Finding their production philosophies to maximise productivity and deliver high-quality products to meet customer demands. For the flexible concepts in this thesis work is job-shop process flow and continuous flow presented.

2.2.2.1 Job-shop process flow

The layout of a production facility plays a crucial role in the efficient movement of materials and products from one point to another (Holweg, Davies, De Meyer, Lawson, & Schmenner, Manufacturing processes, 2018). A poorly designed layout can lead to longer set-up times, disruptions in material flow, increased overhead costs, and hinder expansion plans. It is therefore essential to consider different layout concepts, each with their own advantages and suited to specific production volumes and varieties.

Among these layout concepts, a job-shop layout is after the project concept the most flexible production concept for doing a wide variety of products in significant quantities (Holweg, Davies, De Meyer, Lawson, & Schmenner, Layout, 2018). In a job-shop layout multiple types of workstations can process multiple types of jobs. Each job type can have a distinct processing route and thus the workflow in a job shop is often quite complicated. The heterogeneity and complexity of the workflow creates great difficulties for production planning and scheduling.

The processing of a lot involves a single setup and processing time for each unit, and the lot can only move to the next station when complete (Graves, 2016). Increasing lot size reduces setups but also results in longer processing time and less fluid workflow, leading to increased production variability. Planned lead times correspond to the time allowed for each job at each workstation, including a buffer for queuing and planning flexibility. Longer lead times

increase work-in-process (WIP) inventory but help to smooth workload arrivals, resulting in less overtime.

This complexity in scheduling and planning often occurs in job-shops because a single product often does not generate enough sales volume to justify creating a product-specific array of equipment. A job shop typically has a diverse array of equipment, with some used heavily and others less frequently. For example (see figure 13), product yellow needs to go through processes steps 1,2,5 and 6 meanwhile product blue need to go through 1,4 and 3.

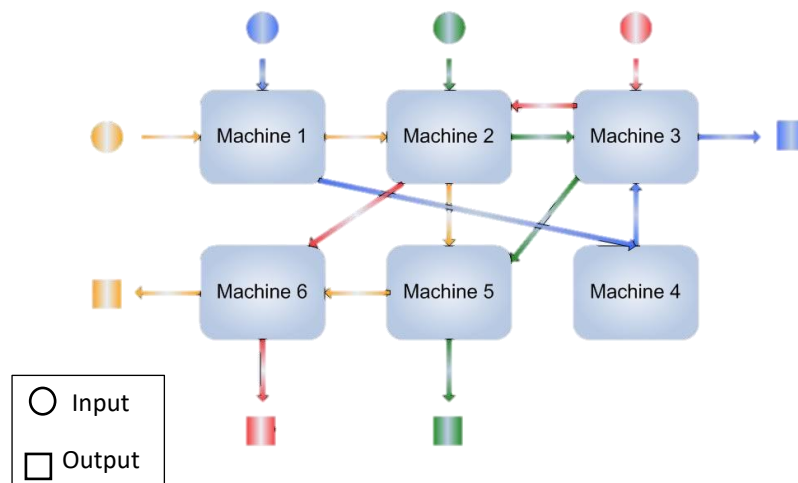


Figure 13: A Job-shop visualisation (Younes2000, 2006).

Manufactures operating with job shops face business challenges when competing for work, shorter product cycles and increased demand uncertainty. Therefore, the information flow has become crucial for a job shop to be effective. Having accurate information about run-times, set-up times, and labor content times can lead to informed bidding and efficient scheduling. Job-shops are good when competing for work and fulfill an outside customer's order by agreed-upon due date a batch flow operation usually produces in established lot sizes that move into an inventory from which further production or final customer orders are filled.

2.2.2.2 Toyota Production System - TPS

The origin of Lean production can be traced back to Sakichi Toyoda which laid the foundation to what today is known as the *Toyota Motor Corporation* and *Toyota Production System* (TPS). In Jeffery Liker's book *The Toyota Way - 14 management principles from the world greatest manufacture* (Liker, The Toyota Way - 14 management principles from the worlds greatest manufacture, 2020) are the enablers behind the Toyotas success as a company discussed and put into context of production philosophies.

In a perfect world will a perfect process exist, perfectly executed and with zero waste. The iconic symbol for this perfect process is the one-piece flow (Liker, Connctet People and Processes Through Continuous Process Flow to Bring Problems to the Surface, 2020), meaning the operator works on one piece and when he is finished will the piece be passed on to the next station, i.e., *continuous flow*. The tools and equipment are required to be lined up in a sequence. Moreover, by leaving the batch production, is also the idea with buffers more

or less dropped and results in a disturbance sensitive process. At a first glance, it seems that continuous flow literally means continuous stop because if problems occur will the whole production line come to a stop. However, when the production halts must everyone involved in the process work together to resolve the problem and the problem cannot hide or disappear in a buffer (for example). Thus, problems come to surface and are forced to be handled. Also wastes are more noticeable in a continuous flow, since e.g., if one operation over-cycles repeatedly and causing to the process to not deliver on time, it might be the cause of waste. The waste must be erased in order for the operation to perform.

Furthermore, mass production in any form is likely to cause increased cost for bureaucracy, governing and for positions, like controllers, for supervising the process. The chance of poor quality is destined to also increase since quality defects are probably discovered later.

The benefits of one-piece flow are several and key benefits are stated below:

1. **Quality is built in.** The operator becomes the inspector and remedy every single problem before passing the product to the next station. If the operator needs assistance, is the *Andon cord* conveniently used to bring on attention. However, if a defect is missed, they will likely be detected quickly. Therefore, is the *quality built in and not inspected in*.
2. **Creates real flexibility.** Shorter lead times means higher flexibility to respond to customer demands. Instead of waiting weeks for a product, if lead times are a matter of mere hours, new and additional orders be filled.
3. **Creates higher productivity.** It is easy to be deceived that productivity is at its maximum when operations are organised by department, since each department is measured by utilization of equipment and people. But how many are “utilized” keeping track and managing inventory or mending quality issues? In the one-piece flow is it easier to see who creating value-adding activities and who not.
4. **Frees up floor space.** Inventories are not required in the same extent and therefore frees up floor space.
5. **Improve safety.** The number of forklifts might be reduced since the material handling is held a strict maximum.
6. **Improves morale.** Improvements and value-added work are immediately observed, giving all a sense of accomplishment and job satisfaction.
7. **Reduces cost of inventory.** Less capital is tied-up in diverse inventories and WIP:s are optimized.
8. **Unleashes creativity of people.** Problems need to be remedy directly as they occurs, challenging people to think and improve.

Liker also highlights the use of pull flow instead of push flow (Liker, Use "Pull" Systems to avoid Overproduction, 2020). Products are regularly forced into the market by companies, such like cloths that are shipped to stores without anyone now if they will be sold or not. In some instances, there are no direct way that is better since if a customer is told that she or he is required to place an order on every clothing item in the shop, they are likely to go to another shop who is able to give the goods instantly. On the other hand, due some clothing

companies base their business idea on precisely that, more specific companies based on the internet. They first receive an order, and then ship it to the customer. The similarities are however relatively big, since inventories are required to meet the demand and that they purchase items on educated guess, i.e., a forecast.

The example above is a typical example of a *push system*, i.e., manufacturing is executed under governance of a master scheduled, that is an educated guess on the further demand. Sometimes the forecasts are more or less spot on. However, the risk of the most fundamental of all waste, *overproduction* (Taiichi Ohno regarded overproduction to be the gravest waste, as it may lead to other wastes), is increased as the customer (could be the next operation in a process) might not need it.

The pull system can be potential solution. In the best of worlds, in a one-piece flow, will the preceding operation produce the part first when a need is created. E.g., a customer enters a car dealership and orders a brand-new car. Even if the customer is excited about the new car, he is willing to wait for the car to be manufactured and shipped to the dealership. At the moment when the order is made, is a work order created and thereby is the order pulled. The order creates a need that propagates through the whole process to manufacture the car (see figure 14). The car is when delivered to the dealership *at the right time, at the right quantity and at the right quality (JIT)*.

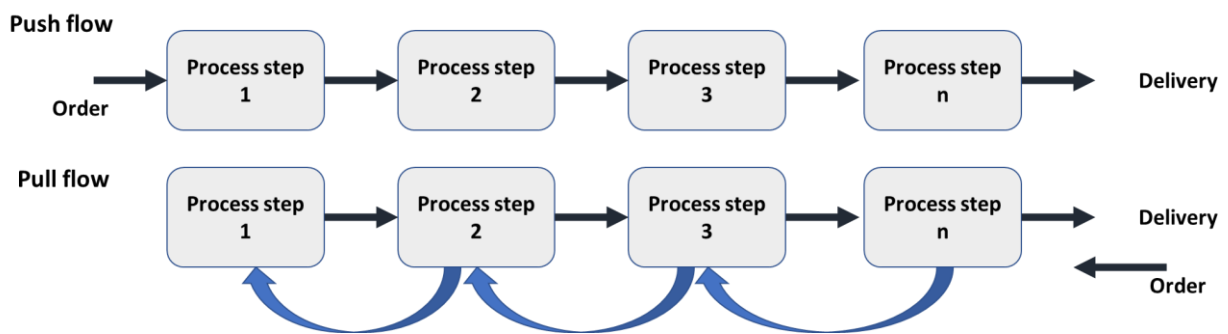


Figure 14: an illustration of push- and pull flow.

How to create a pull system? The answer might be to use *Kanban*, which translates to *signal* of some kind. The idea with Kanban is to show and indicate that a need has been created to the supplier. It can be bins, cards, or flashing signals. However, even if the use of a pull system reduces the inventory, it might still be necessary to keep some since it frankly can be too burdensome to deliver too few articles at the time. The inventory may therefore change appearance e.g., 10-cylinder heads are required in an assembly process every 10 minutes, but 12 are sent instead in order level the number of deliveries and keep a little safety stock against unpredicted events.

An important element of TPS is *standardisation* (Liker, Work to Establish Standardised Processes as the Foundation for Continuous Improvement, 2020). The standardised process is part of the foundation of Toyota Production System and why is that? A group leader on Toyota is likely to respond that total quality with zero defects are reality and the answer of getting there is “through standardization”. When defects are discovered is one of the first questions when trying to find the root cause “*was standardised work followed?*”.

Furthermore, the answer to why standardization is part of the foundation is also because the process must be standardized for continuous improvements to work. This leads directly to the additional question *why*? Hence, if an improvement is made based on a process without standardization or the standard is not complied to the largest extent possible, who know if the improvement was made based on the standard or on a snapshot of the process?

Yet, standardisation is subject of continuous improvements since if a “new best way” is discovered should that be applied instead. According to Taylorism should the best way be established scientifically and when determine one best way to train the worker. The person best suitable of doing the job in that way is then scientifically selected and a foreman is hired to teach and monitor. Lastly should financial incentives for worker be created for following the best way. Is this doable? Yes, but on the expense of large staff groups, top-down control, books of written procedures and rules to comply to and etc.

The standard should be established in close collaboration between engineers, team leaders and operators so that every expect is covered in the standard. Keep in mind by going to the Gemba (Gemba means “the actual place” and foremost where the value is created or where the problem is) and talk to the people knowing the process best, are the operators.

Moreover, standardised work is a goal to work toward and not a tool to implement. Standardisation works like a backstop, stopping the improvement of sailing down after an enhancement.

Quality work is also addressed in the TPS and is referred to as *Jidoka* translates to *automation with a human touch* and goes back to Sakichi Toyoda’s day when he invented the automatic loom, stopping when a thread was cut off (Liker, Build a Culture of Stopping to Identify Out-of-Standard Conditions and Build in Quality, 2020). Instead of keeping producing, the process is halted, and the deviation becomes contained. Prior to Sakichi’s invention, did the loom keep producing and thereby wrecking most of the spruce. By containing the problem at its origin, rather letting an inspection station notice and adjust the problem, is money saved and the process becomes aware of the problem. One should also have in mind that Lean manufacturing considerably increases the essence of building it right the first time. Inventories are generally low, i.e., small buffers between stations and if A stops will B stop soon afterwards.

In order to call on attention, is a signalling system called *Andon* applied. With help of an alarm, signal, or a string of music is the need for assistance proclaimed. Everything that is an abnormality is a reason for pulling the Andon cord, and likewise risking exceed the cycle time or assembling problems are additional reasons.

Applying adequate countermeasures like standardised work, Andon etc, is vital for controlling the quality from fluctuating. Deviations and errors should be investigated properly with the aim for finding the root cause with help of e.g., Lean Six Sigma. Error proofing, or Poke-yoke (fool proofing), with a poke-yoke device is equally important for improving quality. To poke-yoke something could be it is impossible to, for example, place a fixture in a different way than the intended way. Moreover, do not be deceived that quality inspection is a replacement for error-proofing or any other countermeasures. The costly manner of quality inspection is something the company wants to avoid and being required to have an inspection station might indicated too little is made to tackle problems in the process.

Liker stresses that it is easy to forget that automation is tool and not a solution (Liker, Adopt and Adapt Technology that Supports your People and Processes, 2020). In order to increase efficiency has automation been regarded to be an obvious solution but however, automation comes with a high investment cost and less flexible for changes if the market demand changes. Highly repetitive work tasks with a low degree of variation are typically automated, but tasks with high variation are not normally suitable to be automated even if “advance automation” is applied. By now a classical example is the Tesla plant in Fremont (former NUMMI plant, a joint venture between GM and Toyota), at which automation could produce vehicles at a super rate. The assembly was almost completely automated and minimal human touch. The result was everything than successful and the company had to invest in a new assembly line. At the end of the day did the owner Elon Musk admit that “humans are unrated”.

Yet, automation, i.e., robots, computers etc, can be a powerful tool when used right. Computes are for example a potent tool for processing information and if used correctly, can the results help us determine which choice or way we should go when working on continuous improvements.

Heijunka is Japanese for “levelling” and is in Toyota Production System (TPS) referring to levelling of production of both volume and product mix (Liker, Level Out the Workload, Like the Tortoise, Not the Hare (*Heijunka*), 2020). *Heijunka* is probably one of the most contradicting things in Lean since one is asked not to strictly build-to-order and instead have some finished goods inventory for levelling production.

The problem of build in an actual production sequence is products are manufactured intermittently. On Monday is 50 orders made and they are finished before lunch. The workers are allowed to go home, but on Tuesday is an order of 200 received which is more that can be done on one shift. Therefore, is the company forced to pay overtime to meet the customer demand. One can instantly see the problem. First, everything is fine but all the sudden are you sent out on a wild goose chase and become overburden. The only way of succeeding is to have piles of inventory, since the customer may order *A* or *B* the next day, problems remain unseen and the workforce is overburden.

By instead using the actual demand combined with forecasts, can a pattern of the volume mix be determined, and a levelled production scheduled is formed. This is frankly called levelled, mixed-model production but nevertheless, inventories are required to a limited extent. Still, the production must be of the type “pull” in order to avoid overproduction (see preceding principle).

The methodology of *elimination of Muda, Muri, Mura* (the “three M:s”) is fundamental of achieving *Heijunka*. *Muda* (uselessness, waste) includes the seven plus one wastes and focus on reducing basically waste. Yet, even if wastes are eliminated can still unevenness exist and directly leads to *Mura*. Unevenness in production results and machine utilization makes it necessary to have material, personnel and equipment for the highest level, even if the average requirements are far less. The lesson is *unevenness leads to too little work sometimes and overburden at other times - leading directly to Muda*.

The third *M* stands for *Muri* and translates to *overburden*. The unevenness might cause lack of work but on the other hand cause pushing the equipment and employees beyond natural

limits to meet demand. Overburdening of people cause problem with sustainability and quality. Overburdening of equipment and machines causes breakdowns and defects. *Mura* can lead to *Muri*, which can cause *Muda*.

The company must work with all three M: s in order to succeed. *Muda* is often easy to spot and eliminate, but creating stability and evenness is equally essential in creating a true, Lean flow of work.

2.2.3 Automation or not?

The choice of machine and equipment is a large determinant in the unit cost of production (Holweg, Davies, De Meyer, Lawson, & Schmenner, Scale, scope and complexity , 2018). Technology can provide economies when a production scale. Automation is a commonly used term for replace manual tasks with robotized process for making the same job. There is upside with this replacement like for example drastic reduction of unit/cost, which is technology-related economy of scale but there are also drawbacks.

A production line with higher degree of automation is more rigid cause of the equipment dedication to one or few products. Automation will reduce the flexibility. Though automation the flexibility of the plant's approach to perform reduce but in many cases, it will increase the capacity to produce product variety. One specific difference between robots and labour are the geometry of the process and required area. For large-process technologies dealing with materials like chemicals or liquids there is a rule of thumb called "6/10 rule". A doubling of volume lead to approximal 6/10 increase of surface area and thus costs. An oil refinery is an example but for "non-free-flowing materials", the estimation needs to be more specific.

The pace of production shifts from worker discretion to management option and the car assembly line is a classic example of labour specialization and (that is, mechanical) management pacing. Moreover, speed or quick throughput time is nearly always more powerful than scale and more competitive. To summarize there is two areas to carefully take in account according (Holweg, Davies, De Meyer, Lawson, & Schmenner, Scale, scope and complexity , 2018). The first one is the cost reduction a company claims it can achieve through specific changes in a plant's volume, capacity, or process technology. Secondly are what those changes may mean management control, logistics, inventories, or the ability to respond to product or process innovations.

2.2.4 The complexity challenge

Complexity, a common word but still generally poorly understood (Holweg, Davies, De Meyer, Lawson, & Schmenner, Scale, scope and complexity , 2018). Often used as a synonym to difficult, those it is a well-defined concept. It includes of two levels, static complexity, and dynamic complexity. Static refers to number of nodes and connections in a network meanwhile dynamic refers to the interaction taking place between nodes in the network. Both concepts directly apply to process design and whereby a process become complex in a variety of ways.

Static complexity is caused by:

- Different inputs
- Different outputs
- Process steps that may lead, also, to long throughput times
- Inventories of one type or another.

Dynamic complexity is caused by:

- Customer interaction with the process
- Different supplier with a wide variety of different supply contracts
- Different components to the products and complex “recipes” for how they combine to produce the products.

The subsequent definition of complexity is based on the fundamental distinction a complex system and the in decomposability of elements. In other words, all elements need to be present for the whole to work. That no element is tangential or reductant. Complexity is naturally related to growing operation, so it is not bad. Some of it is needed to satisfy the divers of customer needs and the key is instead balance benefits with its cost and eradicating non-value-adding complexity. Dealing with complexity can mainly be done through to simplify and thus reduce complexity in the first place and to increase the organization’s ability to cope with the complexity at hand.

This segment can be summarised: “A comparable, yet simpler solution will always outperform a more complex one in the long term”. (Holweg, Davies, De Meyer, Lawson, & Schmenner, Scale, scope and complexity , 2018).

2.2.4 Incorporating product development in manufacturing – DFA and DFM

Products designed and developed by the companies Research and Development departments (R&D) might comply to the laws of physics and withstand the intended forces and areas of application. However, products must not only comply to forces and the application area but must also be able to be assembled and manufactured, preferably in a straightforward manner. Problems related to difficulties assembling products can lead to quality issues and redundant use of material, resources etc. and in the 1980s were the methods *Design for Assembly* (DFA) and *Design for Manufacturing* (DFM) developed by the American scientists Geoffrey Boothroyd and Peter Dewhurst (Johannesson, Persson, & Pettersson, 2018). The methods aim to early identify were potential assembly or manufacturing problems might arise in suggested concept solution since late minute changes entails costly and many times burdensome work. Hitachi is one company utilising DFA and has the ability to already in the initial product development phase estimate the cost of assembly.

DFA can be applied for all kinds of assembly operations e.g., full manual or semi-automatic assembly, and the first step is to identify which assembly method is most appropriate in relation to the production volume. A requirement is that the assembly sequence is broken down into elementary operation, e.g., pick up the detail, place the detail and so on. The

method developed by Boothroyd and Dewhurst when stipulates if it possible to eliminate components and details by judging each component against following questions:

- Is it feasible to completely eliminate or combine the detail in question with another?
- Must the detail be movable in relation to other details?
- Is the detail a requirement towards material selection or the possibility to assemble other parts?

The proceeding steps is to estimate the total assembly time for each detail. In the final step is the assembly efficiency calculated. The number is however an approximation but can still provide engineers with adequate support whether adjustments need to be done or not.

DFM is described as a mind-set and philosophy where knowledge connected to manufacturing operation is incorporated in the early stages of design and product development (Poli, 2001). Known issues should be addressed explicitly in relation to how it may influence design, such as unwanted heat leads to material changes, and moreover should consideration concerning tooling cost, assembly cost, work environment etc. be discussed. The key understanding regarding DFM is that it is an iterative tool, hence it should occur throughout the design phase from the initial outline to the final concept decision.

2.3 Investment assessment

As a profit-making company Aurobay seeking return on their capital and how to invest payments for increase their future profit. Return on capital can be made through investing in new technology but also by putting the capital into the stock market. During an investment assessment a discount rate is a normal tool to analyses if the investments in the own company compared to the market gives more profit. This discount rate can be different depending on which index you compared to as requirement on return. An example is the OMX Stockholm 30 that include the 30 biggest companies at the Stockholm stock market, which has given around 8,5% last 30 years. A discount rate at 8,5% (OMXS30, OMX STOCKHOLM 30 INDEX, (SE0000337842), 2023) (OMXS30, OMX STOCKHOLM 30 INDEX, (SE0000337842), 2023). Investments are decision consequence reach over multiple years and investment projects initiate, drives, and been followed up in a context of market, competitors, company strategy and capital. (Andersson G. , 2019). Therefore, it is hard to predict the future, but calculate the final value and net present value can give a prediction if the investment gives a good yield. Estimating the investment's profitability over time by the final value and net present value, entails adding up the investments at year zero and subtracting yearly costs from yearly payments. A positive net present value indicates that the investment will yield good returns. Moreover, the payback time can be computed by dividing the total investment by the average annual cash flow. For example, if the total investment is 10,000 crowns and the yearly cash flow is 2,000 crowns, the payback time will be five years.

2.4 Advantages of simulation

Simulation means representing a system with another system to study its dynamic behaviour or practice mastering the system under laboratory conditions (Nationalencyclopedia, 2023). Simulation is used when the studied system is either too complex, expensive, or too dangerous to study for real. By simulate a system can hidden problems and interaction surface earlier and thereby save both time and money. Simulation can explore different scenarios and predict outcomes without having to conduct these expensive or risky experiments in real life. Modern simulation employs mathematical models that include fundamental laws of nature, geometry, and material properties. These models are typically represented as systems of differential equations, which are solved numerically using computers. These simulations can also support in optimising production process and find bottlenecks in a system. A risk with simulations is that they can produce uncertain results due to high variability. Previously, variants reduction methods were employed, but today by generating many observations with fast random number generators, a more practical and effective solution for obtaining more accurate and reliable outcomes are done. This approach is widely used in modern simulations.

3. Project scope, project charter and limitations

The agreed project charter is a product of the define phase. limitations concerning topic, deliverables, and team jurisdiction. Additionally, is the project scope defined, i.e., research questions and goals.

3.1 Project limitations

The project should primarily focus on cylinder heads, cylinder blocks and the bearing bracket, which are milled. Other products also machined at Aurobay are cam- and crankshaft but are not covered in the project scope. However, the limit shall not be viewed as a strict limitation and findings and development along the journey rule them out.

Additionally, product development and other similar activities that normally falls under Research and Development (R&D) is not covered in the scope of the project. In other words, the project will not develop e.g., new designs of cylinder heads etc. Moreover, a yearly production volume range of 10 000 to 30 000 has been stipulated by Aurobay and the scope of production is from the entry of raw material at the beginning of the line to a finished machine part at the end of line, e.g., supply chain to and from the factory and final assembly are not part of the scope. Yet, asked by the main stakeholder, Aurobay, the project should not limit itself too much and the findings should determine the outcome of the project.

Furthermore, the team does not have any jurisdiction to implement, invest etc. in project outcome and only present recommendations.

The last limitation is set by the university, Chalmers, concerning the expected time spent by the team. Time is governed by the university credits, which in this instance are 15.

3.2 What should the project achieve?

The project aims to deliver low production concepts for machining operations, through comparative analysis between concepts with different characteristics and set ups. The characteristics were identified in voice of the customer as:

- Three lines manufacturing one product with 10 000 in yearly volume.
- One line with flexibility of manufacturing three products with 30 000 in yearly volume.
- Products of interest is cylinder block, cylinder head and bearing bracket.
- Ability manufacture product X, in other words a product not yet in production.
- Tools and set-up.
- Fixtures.
- Investments.
- Cost and profits.

However, the term flexibility has broad area of application and could therefore imply a wide range of things. The team must enquire how the customer defines and what is expected from a flexible production concept.

Hence, the project research goals and deliveries are as follows:

- a. Define and develop an understanding of what flexibility is in relation to customer expectations.
- b. Deliver machining production concepts capable of manufacturing low volume according to characteristics identified in voice of the customer.

3.3 Project charter

The project charter is presented in table 5. For project plan, please see the appendix.

Table 5: the project charter

Project charter	
Flexible machining concepts	
Business case	The automotive market is undergoing change in demand which requires a new approach for low volume production. With new methods and angel of attack will Aurobay increase their ability to meet the demand of tomorrow.
Project formulation	Flexible machining concepts for low volume
Team members	Ludwig Almedal and Oscar Ivarsson
Project plan	See Gantt schedule
Tollgates	See Gantt schedule

4. Methodology

In the *Methodology* chapter is research method and approach, *Six Sigma*, explained and the chapter shall be regarded as a *how-was-it-made*. The Six Sigma methodology is highly data driven.

4.1 Six Sigma

The Six Sigma methodology was first developed in the 1980s by the electronic equipment and components company *Motorola* (Bergman, Kroslid, & Magnusson, Appendix B - *Motorola, the cradle of Six Sigma*, 2002). Motorola had in the end of the 1970s learned that their Japanese competitors had significant advantages concerning quality and customer satisfaction, and the potential of losing clients were a reality, and the problem did not pass CEO at the time Robert W. Galvin without notice, who in 1981 rolled out a bold ambition for the company to improve the quality be ten times over a five-year period. At first were Joseph M. Juran and Dorian Shainin put on the job of trying to identify, work and solve the most grave quality problems by applying statistical improvement strategies like *Statistical process control* and *Design of Experiments*. Despite their efforts and an initial saving of 6.4 million USD at the end of the five-year period in 1986, Galvin and his management team were still worried over the Japanese superior quality work and Galvin stated “*Quality was like a religion over there. It's a whole different sense of urgency*”. Hence, the pace was stepped up by launching a new improvement program, deciding that process performance should be improved to 3.4 defects per million opportunities (DPMO), i.e., *six sigma*.

The new quality improvement program was named Six Sigma and the program emphasised three major deliveries:

- a. Improve quality regarding products and services 10 times by 1989.
- b. Attain a least 100-fold improvement in 1991.
- c. Process performance should reach six sigma by 1992.

In order to ensure the success of the program were employees at all levels educated about process variation, its effects and the necessity of reducing it and significant progress was reported. When the set-up deadline in 1992 was reached had the Six Sigma methodology become a success story with cooperate savings of over 2.4 billion USD and awarded with the highly regarded *Malcom Baldrige National Quality Award* and *Nikkei Award*.

Fortunately, are two Six Sigma improvement methodologies formalised and stratified depending on project type. Process improvement project follows the DMAIC methodology, where DMAIC stands for *Define, Measure, Analyse, Improve* and *Control*, and DMADV methodology (*Design, Measure, Analyse, Design* and *Verify*) for design improvement project. The five phases are interactive, highly data driven and systematic, which are highly regarded attributes within project management and process improvement. The two of them have obvious similarities but however, DMADV is mainly focus on enhancing and refining existing design of products, processes and systems (Bergman, Kroslid, & Magnusson, The

Six Sigma framework, 2002). Consequently, DMAIC offers a more suitable approach when developing a new process systems and methods.

The five phases entail sets of several activities, tollgates and steps, but every tollgate etc. may not be necessary to comply or fulfil to (Bergman, Kroslid, & Magnusson, Process improvement, 2002).

The *define phase* coherers of the four tollgates:

- Generate project and prioritise.
- Identify y or y:s to be improved/understanding the voice of the customer/benefit assessment.
- Determine performance or process map/effective scoping
- Develop project- and team charter/define problem and project scope.

In addition is the define phase regarded as the most important of all steps since if the scope of problem or improvement opportunity not is fully understood, could the project be in jeopardy of missing or solving the wrong issue or have a too narrow approach.

In the first tollgate should identify improvement opportunities and prioritise in order of importance to the business which should be addressed first and pareto charts are typically helpful for ranking and prioritising project after certain criterions e.g., quality deviations and stopping time. However, the first step had already been done and project team could swiftly move on to the next.

The next step is to understand the *Voice of the Customer*. When performing a DMAIC project, or any kind of project, is it essential to focus on the right issue based on the key parameters of customer satisfaction (Carleton, Voice of the customer, 2018). By applying *Voice of the Customer (VOC)*, which is used to describe needs and expectations stated by customer, is the jeopardy of solving the wrong issue or deliver non-wanted results minimised. The analysis provides methods on how to collect and categorise data from the process and stipulate *Critical to Quality (CTQ)* requirements. The *Black Belt Memory Jogger* entails a seven step how-to-do-it procedure. The steps are:

1. The internal and external customers must be identified.
2. The identified customers might be segmented corresponding to their requirements, internal or external, location, department etc.
3. What information concerning VOC exists already and what must be collected by the team?
4. Decided on the initial data collection method, such as baseline research, interviews and surveys.
5. Collection of VOC data.
6. The CTQ is defined based on the VOC data in terms of customer needs and expectations. Measures, metrics and specifications are created based on the CTQ.
7. The primary focus concerning measures and areas are identified and validated by the project owner.

When performing a DMAIC project will the *project benefit assessment* help to determine the value of the project and then in time the benefits will show. The benefits identified in the define phase should be used as an input when analysing the proposed solutions in the

improve compared to the cost against benefits. Moreover, could normally benefits be categorised into *hard* respectively *soft* benefits, i.e., benefits directly measurable in financial value and those benefits not immediately noticeable in monetary values but are however valuable for the company.

Another tollgate is to determine the current process performance and/or map the process. By properly map and determine the current process performance could the potential cost saving be known as well as other important information regarding the process (Bergman, Kroslid, & Magnusson, Process improvement, 2002). Map the process could also include a comprehensive background research regarding underlying aspects inflicting on the project or of current methods and in thinking. The team applied *Effective Scoping* which is a reworked version of SIPOC (*Supplier, Inputs, Process, Outputs, Customer*) and provides a helicopter overview of the process and helps to determine the elements in the project scope (Zanti, 2015). The method is developed by Peter Hammersberg, PhD and Six Sigma Master Black Belt, after experiencing that organisations found it difficult to acknowledge the metric to improve. On regular basis the customer or context requires the output to satisfy more than one requirement, denoted big Y, and every requirement can frequently be measured in multiple different ways, denoted small y. By using effective scoping one can make sure that the measure to improve in fact is the correct measure of what the customer really wants, thus avoiding running to a conclusion or a poorly formulated task. The tool should be executed in a nine-step sequence.

Lastly should a project scope and project charter be set. The project scope stipulates *what* and *what is not* covered in the project, i.e., limitations, delimitations and constraints, as wells as deliverables and desired outcome. In other word is it a conclusion and summary on the proceeding findings. Moreover, the project charter contains *why* the project is executed (business case), short description, team members, project plan and deliverables throughout the project.

In the *measure phase* is the first activity to identify how the y:s are influenced by a number of x:s a *cause-and-effect diagram (fishbone diagram)* is drawn to visualise the relationships. The cause-and-effect diagram is applied multiple times since it helps to indicate and reveal causalities. It is important to notice that the x:s could be both controllable, i.e., signals, or the noise. The main difference between them is that signals can be controlled in contrary to noise that are uncontrollable or too costly, or non-desirable to control (Bergman, Kroslid, & Magnusson, Process improvement, 2002). However, they need to be measured and in other words collected. The measured and collected data can be both qualitative and quantitative. Qualitative data consist of interviews, diaries, open survey questions, audio-and visual recordings and other non-numeric information. Quantitative data is on the other hand numeric and countable, such as measurement readings of an industry process or the speedometer in a car. The interviewees were selected to represent the research field and span of experience at the company. Interviews might be ad-hoc meaning that they are not planed in advance or planed. The later suggests that a data collection plan is developed.

The data collection plan ensures correct and relevant data is collected. Since progress in a DMAIC project is highly dependent on data cannot the need for data be stressed, but it is on the essences that the data not just correct and relevant, it is equally important that the data is

collected the right way. The plan should stipulate *what-* and *what not* to be included and methodology on *how* the measurement process is executed, guaranteeing data consistency and reliability. The Black Belt Memory Jogger entails an eight step “*How to do it?*” guide and is applied by the team throughout the course of the project (Carleton, Data collection plan, 2016).

The eight-step guide is as follows:

1. The data of interest is required to be specified
2. Establish a definition on what the metric is supposed to represent, and how the metric is measured i.e.,
 - a. What is included?
 - b. What should not be included?
 - c. In what unit (e.g., km/h, kg etc) and resolution should the metric be in?
 - d. Triggers
 - e. The physical measurement
 - f. Calculations
 - g. Storage of data
 - h. Reporting
3. The specification limits, the precision of the measurement- and capability
4. Who is responsible of collecting the data?
5. Frequency and timing of the data collection
6. Specify sample size and subgroups
7. Where is the data is stored
8. Interact and keep relevant people updated and review the plan as needed.

A template was developed and used throughout the duration of the project. See appendix for the data collection template.

Collected data is processed in the *analyse phase*, where the data determines how the key inputs affects the outputs. In order to come there is the reasonable starting point to get know the y:s previously discovered in the define phase and quantitative data is interpreted by reviewing the standard deviation and mean value, how y is distributed, performance in terms of DPMO and predictability (Bergman, Kroslid, & Magnusson, Process improvement, 2002). Qualitative data, on the other hand, is decoded with *graphical analysis*, *process maps* and so on. However, tools like process maps are of course viable quantitative data as well and should be regarded as a complementary tool for visualising.

The subsequent step is to identify the x:s influencing the y:s. Suitable and effective tools for identifying x:s of influence are *cause and effect diagram* (sometimes referred to as *fishbones diagrams*), *tree diagrams*, *relationships charts* and *stratification*. Additionally are analysis like correlation-, relationship- and ANOVA powerful tools when decoding. By revealing which x:s influencing which y:s are also potential root causes identified.

In the proceeding *improve phase* are potential solutions identified and design according to the gained knowledge from the analyse phase (Bergman, Kroslid, & Magnusson, Process improvement, 2002). A benefit analysis for every presented solution should also be made and with regard to the benefit analysis made in the beginning of the project and besides, if

needed, should a revised process map and *Failure Mode and Effect Analysis* (FMEA) also be done. Depending on the project is *design of experiments* (DOE) recommended to study the how effects of inputs (factors) and input interactions influences the process output. The solutions should also be validated by running simulations and/or with PDCA pilot studies. PDCA. Finally shall an implementation plan be presented, responsible for governing *how* and *when* (Carleton, Improve Phase, 2018).

The last phase is the *control phase* and where the planned and implemented solutions are verified according to the predefined values and desired performance level (Carleton, Control Phase, 2018) (Bergman, Kroslid, & Magnusson, Process improvement, 2002). Improvements related to process performance is conveniently controlled with, take for instance, control charts, but other suggestions not directly linked to numeric values (quantitative data), e.g., change in instructions etc., generally requires another approach. For instance, the performance of how changes to an instruction could be measured through comparing the quality result prior to the change and the result after. An important step in the control phase is to *standardise, document, communicate* and *visualise* the plan in order to create a common ground and consensus regarding the project outcome. Lastly should an estimated cost saving and final project assessment be presented before the project is closed.

4.2 Literature study

The purpose of literature studies is to frame and understand where the limit of knowledge is today within the field. Literature used has been journal articles, reports, thesis works, books and articles in periodicals supplied by Chalmers library among others. Key search words where *production flexibility, flexibility, Volvo Skövde, Volvo Cars Skövde, Volvo, sustainability Volvo, production philosophies, Toyota Production System, job shop, industrial automation*.

5. Results

The results chapter is the collected data presented.

5.1 Flexibility

5.1.1 Qualitative data collection

The team identified both qualitative and quantitative data were required when defining flexibility, there interviews and hearings made up the qualitative part while quantitative data is collected from a kappa analyse. Hence are two different collection plans required (see figure 15 and 16).

Project		Flexible machining concepts - thesis work									
Project team		Ludwig Almedal, Oscar Ivarsson									
Description		Qualitative data collection - interviews									
What does the data represent and how is the data collected?						Execution plan					
Unit	Is the data an input (Y), output (X) or process?	Measurement system	Lower spec. limit	Upper spec. limit	What and how?	Responsible	Frequency	Sample size	What do the subgroups represent?	Data storage	Data reporting
Numbers of interviews	Y	Interviews	N/A	N/A	Predefined questions: <i>What is flexibility according to your own experience?</i> <i>If you are asked if your process is flexible, what would you point at?</i> <i>What is the vision in your process?</i> Answers are noted in a notepad/computer and transcribed to a Word document.	Ludwig & Oscar	Weekly and monthly. From mid January to April	One person is equal to one sample. Approximately 2 personer a week	N/A	Word document, stored at the team's Team	The data is reported in the final project report

Figure 15: data collection plan for interviews.

Project		Flexible machining concepts - thesis work									
Project team		Ludwig Almedal, Oscar Ivarsson									
Description		Kappa analysis, part of defining the term flexibility									
What does the data represent and how is the data collected?						Execution plan					
Unit	Is the data an input (Y), output (X) or process?	Measurement system	Lower spec. limit	Upper spec. limit	What and how?	Responsible	Frequency	Sample size	What do the subgroups represent?	Data storage	Data reporting
N/A	X	Survey	N/A	N/A	<p>Survey consisting of seven cases. The case presents a production flow which has certain, predetermined characteristics and the person answers if the flow is flexible or not (yes/no). The survey person is invited to a meeting where the purpose of the survey is explained. The survey is then answered individually. Three different groups, <i>assembly, machining & support function</i></p>	Ludwig & Oscar	Mid March to April	20-25	Difference between each main group	First in survey program where the results are collected. The results are then transmitted to JMP software	The data is interpreted in the final report where the result is analysed and weighted against other measurement findings

Figure 16: the data collection plan quantitative data.

5.1.2 Interviews

The term flexibility was up for discussion during several interviews with both management for assembly, machining, and support functions. The interview tool is used to collect opinions and thoughts from these sessions in a qualitative manner by applying *Kinship Charts*. The Kinship diagram is a chart outlining relationships in a family, society, or culture. In many ways, the Kinship diagrams are like family trees, but instead of listing specific names or modelling the diagram after one family, Kinship diagrams are used more generally. This chart gives the basis for improvement work, create a common picture, develop relations and teamwork as well as create more participation in improvement work (Bergman & Klefsjö, *De sju ledningsverktygen*, 2020).

The first step in this process is to gather the research group together for mind storming or as in this case collect all the data from interviews from Aurobays employees at several departments and professors to answer the question, “*What is flexibility and what is important?*” and “*How can it be measured?*”.

In this Kinship Chart the question is about flexibility and due to some differences in measuring between the normal Kinship chart analysis and this analysis, it is a little bit twisted from the theoretical method. This question was answered verbally by interviews instead of each participant writing down the answers on sticky notes (see figure 17) and therefore these answers from step 1 has instead been visualised by doing sticky notes afterwards. The answers on the sticky notes are collected from interview and literature studies: (Hammersberg, 2023) (Cylinderhead, 2023) (Jonsson, 2023) (Andersson L.-Å. , 2023), (Assembly, 2023) (Almström & Vecchiattini, 1996) and (Salunkhe, Towards Increasing Operational Flexibility in Final Assembly using Industry 4.0 Enabling Technologies , 2021). The key outlines from literature studies regarding flexibility were also included since the method offered a way to accumulate and compare all findings related to flexibility.

Step 1

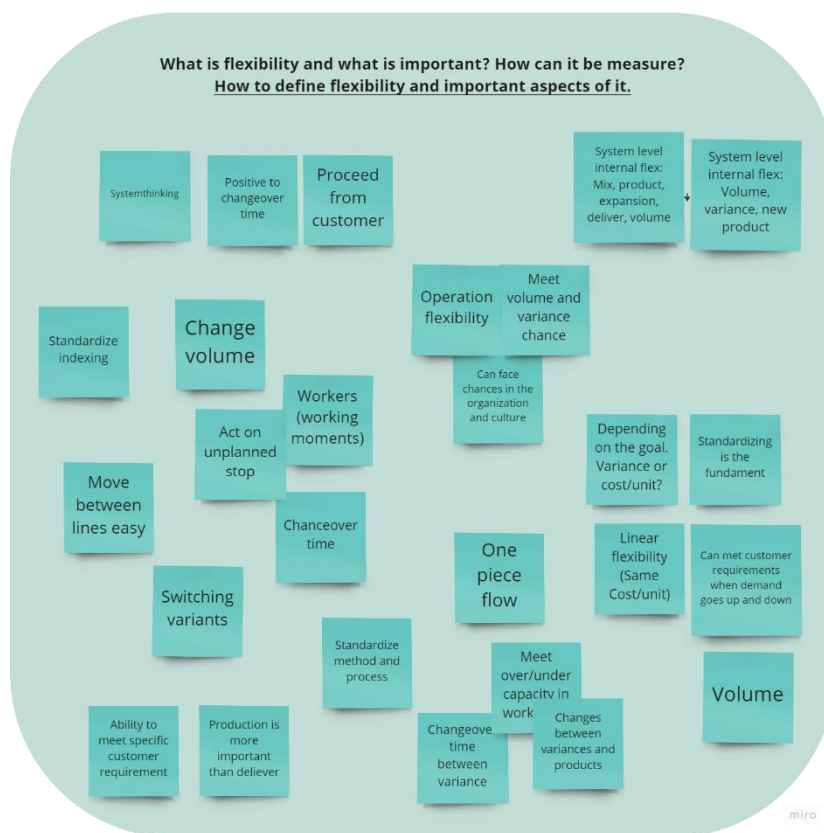


Figure 17: Step 1 in Kinship Chart, brainstorming about what is flexibility, what is important, and can it be measure?

In the second step (see figure 18) is the number of notes reduced by deleting duplicates. After the second step rubrics should be set to connect notes to subgroups with common topics. These rubrics can be set by the project leader or discussed during the session. After the reduction, it will probably be some “lonely wolves” that are hard to put under a rubric and to avoid rubrics with only one note these can be under the rubric “general”. For example, “one piece flow” and “act on unplanned stop”.

Step 2

What is flexibility and what is important? How can it be measure?
How to define flexibility and important aspects of it.

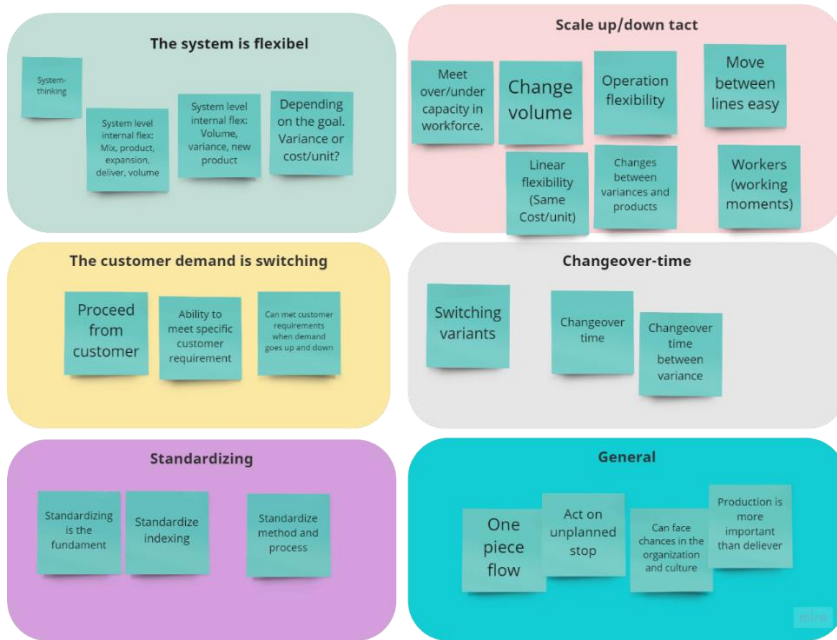


Figure 18: Step 2 in Kinship Chart that sort out notes into subgroups and set a common rubric for each one.

The third step (see Figure 19) is to rank what is most important for the rubric/subgroup but also (if possible) to connect subgroups to each other. This is because some subgroups can be an underlying cause for others. For example, in this case standardising is an underlying cause for several groups such as scale up/down tact time and changeover-time (Bergman & Klefsjö, De sju ledningsverktygen, 2020).

Step 3

What is flexibility and what is important? How can it be measure?
How to define flexibility and important aspects of it.

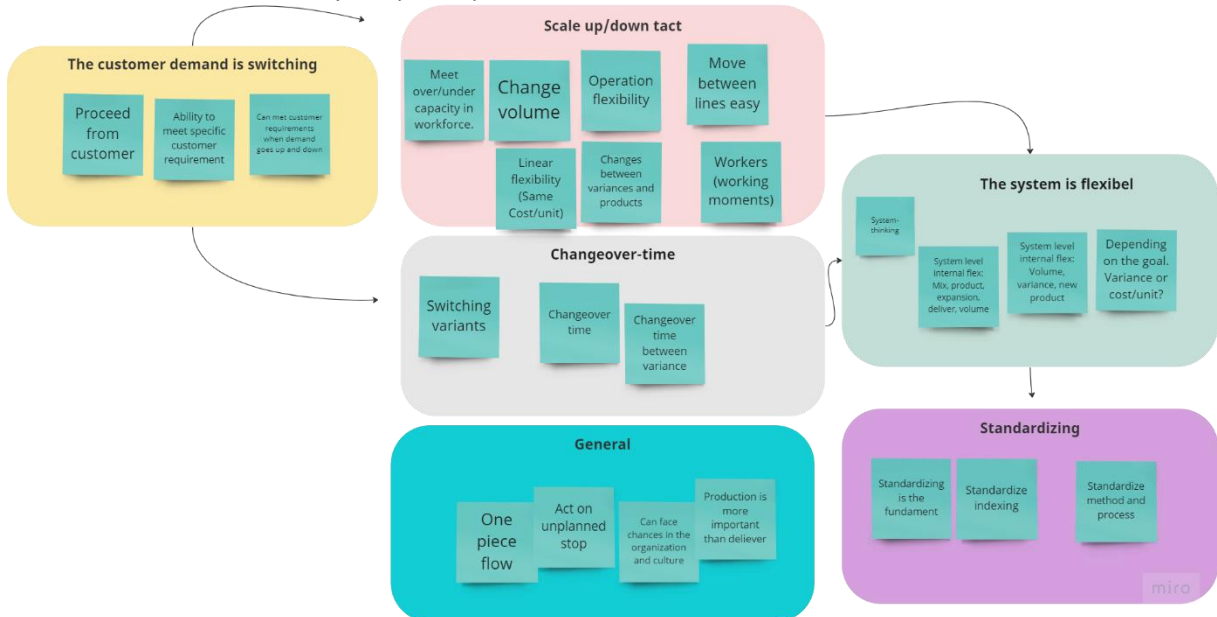


Figure 19: Step 3 of Kinship Chart that connect rubrics/subgroups.

5.1.2.1 Key outline from interviews

The interviews and Kinships Chart provided valuable insights into the concept and understanding of flexibility in the production process. The key takeaway was that flexibility is essential for business to meet the changing demand of customers in the future. However, defining and measuring flexibility is not straightforward and down below are the analysis from the interviews.

Firstly, most thoughts were about scale up/down the takt time, e.g., having the ability to manufacture different volumes of a given product based on the demand. Secondly, in interviews for the stick notes, working movements that are easy to understand is an important aspect for a good flexibility as well as meet over/under capacity in workforce. Thirdly the analysis of interviews concludes that flexibility is hard to define but also it is almost impossible to measure in a suitable way. Changeover time can be measured but is often specific to a certain machine or certain tools. System thinking and standardisation are lifted during the interviews as key performance index but cannot be measured in an easy way. Thirdly, the definition of flexibility starts with a customer demand that is changing. For instance, an increase in demand for petrol engines and decrease in diesel engines from one month to another, which makes scale up/down besides good changeover-time important in production but also operation flexibility in width of what can be produced. A company capable of scaling down production is also ready for new demand for products. Lastly, after sorting out the term flexibility completely, is standardising the fundamental part of good flexibility. System thinking is also central behind handling scale up/down and changeover time but to succeed with system flexibility standardizing is needed according to the interviews. If the process is standardised the way the process is mapped and understood. Likewise, it makes it easier to understand how it will be affected by the new demand. Both machines and the workforce know how to handle more variants and products when the process becomes standardised.

To summarise key outlines is changeable production volume and having the ability to scale up and down by applying standardise work and system thinking, flexible production can be possible.

5.1.2 Visit at Volvo Trucks Tuve plant

In order to broaden the perspective and providing supplementary views concerning production and flexibility the project team visited Volvo Trucks production facilities in Tuve, Gothenburg on the 22nd of March 2023. Production at Volvo Trucks Tuve plant started in 1982 and employs over 2700 people. The heavy-duty trucks manufactured by Volvo today are the FH, FH16, FM and FMX and the Tuve plant is CO₂ neutral. Besides, the factory supplies other company factories trucks frames member (AB Volvo, 2023). Questions had been prepared in advance and the answers as well as discussion are presented below (Strand, Werda, & Sand, 2023).

The team was welcomed at the plant in Tuve by Robert Strand who has started his career at Volvo Trucks back in 1995 as final assembly operator. He has since then worked with automated guided vehicles, used at the plant, and has been part of the electric truck project, but has now become technical manager.



Figure 20: standing from left, Charlie Sand, Tania Werda and Robert Strand. Photo used with permission from Volvo Trucks.

The visit started with a guided tour of the plants final assembly which provided a thorough overview of the process and process methodologies and the team got an understanding of the of products manufactured. After completing the tour, the team was given the chance to ask question to both Strand and two of his *Local Area Specialist (LTS)*, Charlie Sand and Tania Werda (see figure 20). A LTS is assigned an area in the factory and the main focus of a LTS

is the daily operation of the assigned area, working with upcoming projects and having contact with the other Volvo Group's truck plants.



Figure 21: the project team standing in front of a heavy-duty truck at Tuve Plant. Photo: Charlie Sand.

When asked “*what is flexibility according to you?*” all three stress the ability to manufacture a wide range of products and variants in the same production line, i.e., both trucks powered by internal combustion engines (ICE) (diesel and biogas) and battery electric vehicles (BEV). They tell the team that all trucks at end of line have been assembled in one flow and adds that a flow not capable of producing more than one variant or product is to be regarded as dedicated. Questions are immediately raised concerning how it is made possible and the interviewees highlight the importance of linearity. Linearity means uniformity between products and variants, and the assembly time is equal at the main flow regardless of product and variant coming down the line. One key enabler behind linearity is the *fishbone principle* (see figure 22), where variation caused by the differences between variants is pushed out of the main line and into the parallel flows (the bones of the fish).

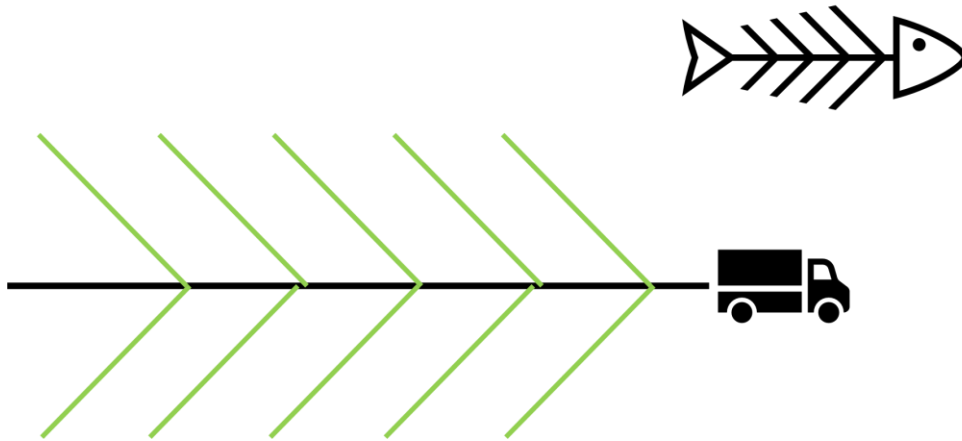


Figure 22: the main flow is feed by parallel flows and to illustrate is often referred to as the fishbone principle.

Additionally, the fishbone principle is further developed by adopting *Mixed Modular Assembly* (MMA). MMA means that for example the powertrains (both ICE and electric) are assembled and prepared as module before being delivered to the main flow (see figure 26), and the MMA thinking is widely implemented as a tool to dealing with variation. Likewise, MMA also makes it possible to level the production and create balance (*Heijunka*). By applying *Heijunka* it is possible to handle volume variation. Materials not being part of the MMA approach, like some wiring, bolts etc., are kitted for approximately three or four trucks in advance and therefore the operator is only presented with the material required not without excess.



Figure 23: the main production flow. A frame of a truck is being processed. Photo used with permission from Volvo Trucks.

Moreover, the interviewees also emphasise standardisation as a flexibility enabler. Tools, machines, fixtures, instructions, workstations and process-and cycle time are all subject of

standardisation and new products and variants are to a great extent adapted to suit the standard. E.g., tools and fixtures are standardised so that the operator does not need to think “what tool/fixture to use now?” and by doing so the equipment efficiency also becomes higher and instructions have a predefined layout in order to make understanding and appliance easier and reduce the risk of errors. Even the process time- and cycle times are standardised according to customer demand but is important when detecting potential variation. Steps identified to exceed the predefined time at the main flow are reallocated to a parallel process to not compromise on main line delivery. Also, there is no set-up time required in the main flow due to the low degree of main flow variation and standardisation. In addition, manufacturing engineering and the *Research and Development department (R&D)* have a close collaboration when developing new products in order that new products can be manufacturing according to standards and avoid costly mistakes, i.e., *Design for Manufacturing* and *Design for Assembly*.

Tuve plant applies working hours that are adjustable to customer demand, meaning that manufacturing is only executed when the demand exist. By letting the blue collars work 44 hours per week is time accumulated in a time bank and if the demand is lower one week, will evening shift on Friday be off duty but in contrary if the demand is high the called, in other words creating delivery flexibility.

The team also asked questions concerning the degree of automation at the plant and was told mainly larger storages and windshield installation are automated. The reasons stated were less maintenance and rigid installations demands prolong lead time if needed to be changed or moved and besides, humans are considerably better at dealing with unforeseen variation. However, torque wrenches and so on are programmed to torque a predetermined value, which is a limited degree of automation. The team also asks question concerning quality assurances and learns that 2 % of the total production in one year undergoes a complete audit in addition to the inspection conducted at the main flow. However, mainly critical components and process steps are inspected on a regular basis.

When asked if it would be possible to manufacture e.g., a Volvo bus at Tuve the answer from all three that is that is too technically complex to do so, due to the difference to the main products, namely the truck, and a realisation of such an undertaking would demand major and expensive modifications.

The key outlines from the visit at the Tuve plant are:

- Flows not capable of manufacturing several variants and products are *dedicated*.
- Erase and push out as much variation as possible to parallel flow (fishbone).
- Use *Mixed Modular Assembly* as a tool to deal with variation.
- Create linearity between products and variants.
- Apply automation when needed and not when wanted.
- Standardisation is one essential enabler for flexibility.
- Work with DFA and DFM.

5.2 Quantitative data collection

5.2.1 Agreement analysis and hypothesis testing

The interviews highlighted, as discussed in earlier sections, potential key parameters, and indicators on what is important for flexibility and what are the criteria for achieving flexibility. Since the factory has multiple departments responsible for the manufacturing processes, e.g., assembly, machining, manufacturing engineering etc., was it necessary to determine whether the departments defined flexibility differently or not. Thus, to see if the definition was altering at the factory the project team applied statistical tools in order to see potential significant difference. Additionally, the team wanted to confirm or reject the interview outcome.

However, statistical tools require either attribute or continuous data in order to display e.g., how variable X relates variable Y, and consequently the team was required to design a quantitative data test. The team recognised that the most suitable data type was discrete (attribute) since the difficulties of design a test consisting of variable data when defining flexibility was identified. Length, time, temperature, weight and so are variable data (continuous), which the project lacked and a test consisting of data with clear boundaries (good/bad, on/off, yes/no, categories etc), i.e., attribute data, was identified to be more able.

The attribute agreement analysis is a method used to determine if the appraiser's judgments are consistent or not and how the judgements vary between appraisers, i.e., repeatability and reproducibility, and is applied when the data is of the attribute characteristic e.g., no/go- and yes/no decision (Carleton, Measurement systems analysis, 2018).

Hence, the team designed a yes- and no question survey based on the outline from the qualitative data collection and three representative departments were identified as sample groups after discussion with the team's Chalmers supervisor, Peter Hammersberg. Moreover, the assembly and machining sample groups were respectively defined as persons part of the management teams and support function as persons part of *manufacturing- or production engineering*. Accordingly, a data collection plan was developed to guarantee the quality of the data (figure 24).

Furthermore, the questions built on cases consisting of machining production flow with varying characteristics and the person taking the survey were presented with the option "yes, the flow is flexible" or "no, the flow is not flexible". The first case was designed to describe "a perfect flow" to then decline in perfection, e.g., case number one has the ability to manufacture several products and variable volume whereas the last case presented virtually having no ability to manufacture more than one product. By just offering two options the judgments between the groups be studied.

All cases are presented in the appendix.

Additionally, the collected data offer the opportunity to perform hypothesis testing in order to analyse the statistical independence of two or more process outputs as well as determine if

alterations to process inputs significantly impact the process outputs (Carleton, Hypothesis testing, 2018).

Project		Flexible machining concepts - thesis work									
Project team		Ludwig Almedal, Oscar Ivarsson									
Description		Qualitative data collection - interviews									
What does the data represent and how is the data collected?						Execution plan					
Unit	Is the data an input (Y), output (X) or process?	Measurement system	Lower spec. limit	Upper spec. limit	What and how?	Responsible	Frequency	Sample size	What do the subgroups represent?	Data storage	Data reporting
Numbers of interviews	Y	Interviews	N/A	N/A	Predefined questions: <i>What is flexibility according to your own experience?</i> <i>If you are asked if your process is flexible, what would you point at?</i> <i>What is the vision in your process?</i> Answers are noted in a notepad/computer and transcribed to a Word document.	Ludwig & Oscar	Weekly and monthly. From mid January to April	One person is equal to one sample. Approximately 2 persons a week	N/A	Word documents, stored at the team's Team	The data is reported in the final project report

Figure 24: the data collection plan for survey.

5.3 Concepts

In this section is the information and mapping for

5.3.1 Mapping and understanding the product similarities and constraints

The production concepts are required to handle three unique products with distinct characteristics and process steps. The distinct characteristics and process steps might impose constraints on how and when the process steps should be executed and whether any other underlying attribute is influencing the process, but on the contrary could certain products features, i.e., similarities, be enablers for making for example manufacturing in the same flow possible.

Today are not bearing bracket (BB) manufactured and for creating a concept with this variable X has the project team picked mass balancing system (MBS) as a substituted. MBS was picked because it is manufactured at the factory and possible to go out and see the production. They are also the same material, similar process steps and size. Though the processes of produce CH, CB and BB include leak test and MBS does not, are leak test not included in the concept of MBS. Leak test is still close at hand with the machine used in CB

and CH, but the project team has followed the value stream map (VSM) and Bill of process (BOP) appurtenant to their product.

Hence, constraints and similarities regarding the products requires to mapped and documented.

5.3.1.1 Bill of process

Today CB, CH and MBS are produced in dedicated lines for each product and the process steps required to manufacture and machine the parts are stipulated by the *bill of process* (BOP). It also informs in what sequence the steps must be executed. By visualising and comparing the BOP for all three products could the process requirements and product constrains concerning the process be identified. The BOP: s is presented in figure 30, 31 and 32. The major similarity between all three products is that they are milled and do not require any turning operations. However, there are several unique process steps in both the way they are performed as well as exclusively performed for just that product. Similar and unique process steps are listed below.

Cylinder block:

Similar steps or characteristics:

- Milling operations.
- Zero-point index (ZPI) for generation three diesel and petrol variants.
- RFID-tags are used for identification in flow.
- Washing.
- Leak test.

Unique steps or characteristics:

- Honing of cylinder stroke.
- Honing of cylinder main bearing guides.
- Classification of bearing type.
- Bed plate and main block requires to be machined separately in the beginning.

Cylinder head:

Similar steps or characteristics:

- Milling operation.
- Washing.
- ZPI.
- RFID-tags are used for identification in flow.
- Leak test.

Unique steps or characteristics:

- Requires two leak tests.
- Assembly of cam cover or cam caps.
- High pressure deburring (HPD).

MBS:

Similar steps or characteristics:

- Milling operation.
- Washing.

Unique steps or characteristics:

- No use of RFID tags.
- No ZPI in use.
- No leak tests.



Figure 25: A cylinder block (CB) of generation 1. Photo used with permission from Aurobay.

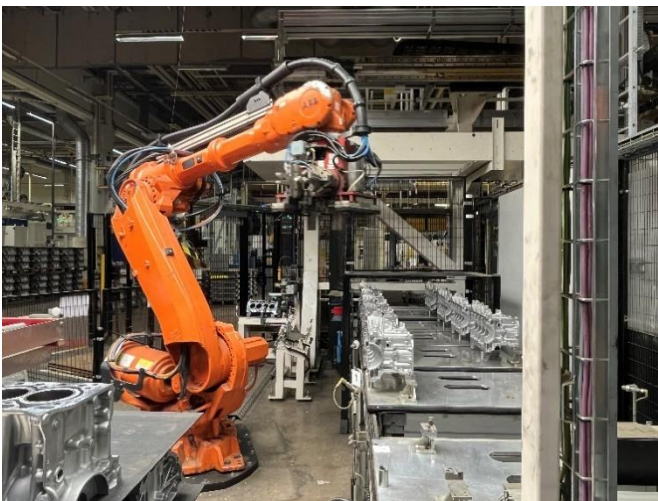


Figure 26: A robot assembl the RFID tag on a Cylinder block generation 1. Photo used with permission from Aurobay.

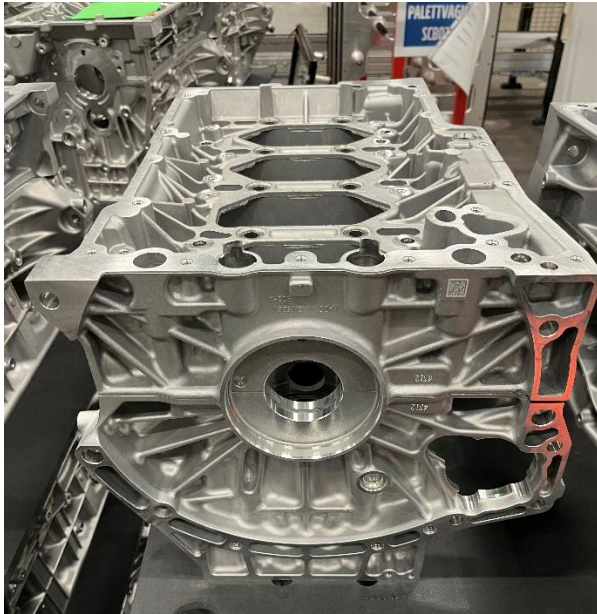


Figure 27: A cylinder block (CB) of generation 3. Photo used with permission from Aurobay.



Figure 28: A cylinder head (CH) of generation 3. Photo used with permission from Aurobay.



Figure 29: A picture over the process of honing a generation three-cylinder block. Photo used with permission from Aurobay.

Furthermore, the similarities between the concepts make it possible to process several objects in the same machine. Before machining anything the objects needed to be identified by a RFID tag (not MBS). RFID tags are for both internal and external use and the internal tag can be removed by the same machine that attach the tag.

Yet, team wanted to increase the knowledge regarding the processes and disclose whether certain steps could be executed in a different manner than today. The steps of main concern were the leak test, *“is really two leak tests necessary for CH and how do it differ from CB leak test?”*, the necessity of machining the bedplate and main block separately and the washing process *“what is the differences between products and variants?”*. A data collection plan was accordingly set up prior to retrieving and measuring the questions (see appendix).

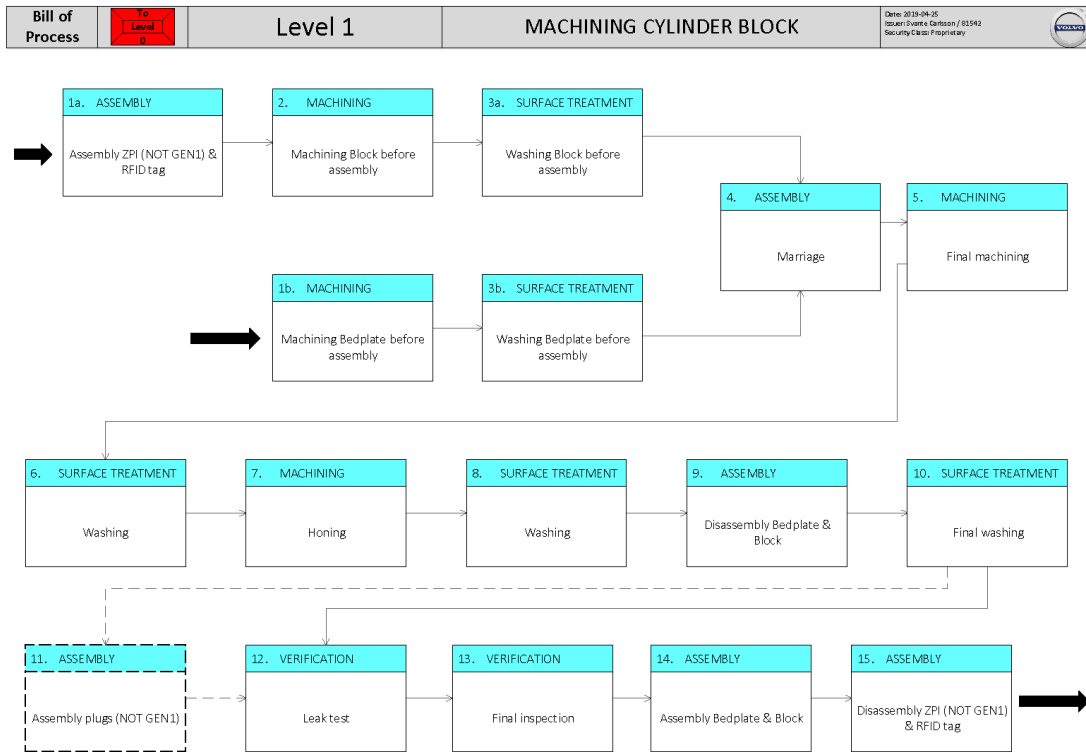


Figure 30: cylinder block BOP.

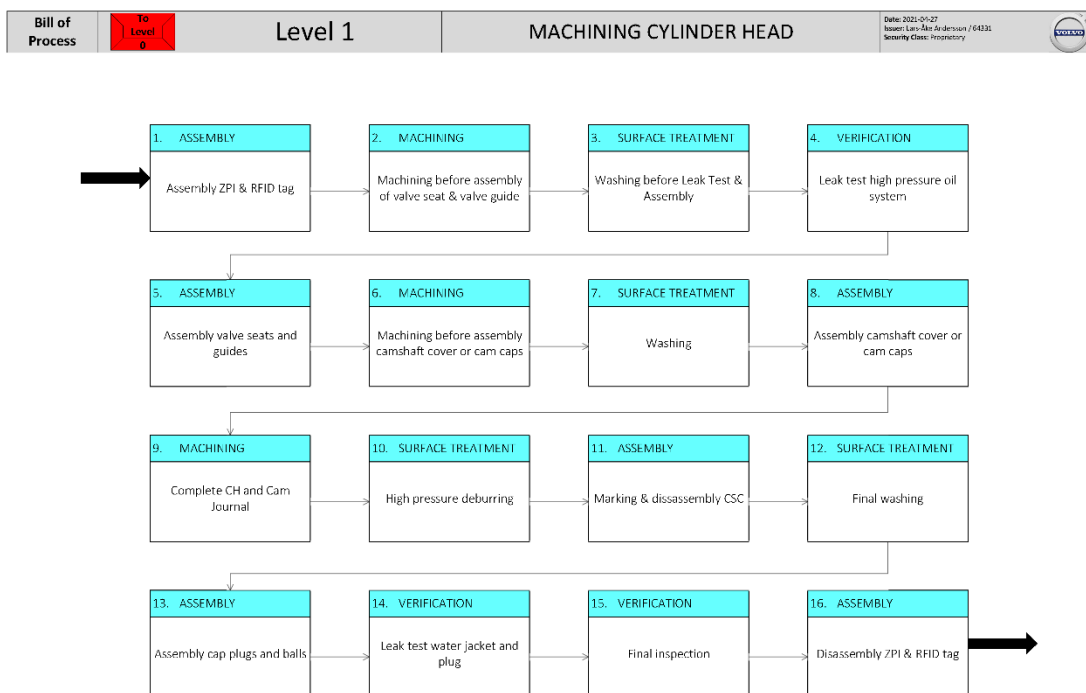


Figure 31: cylinder head BOP.

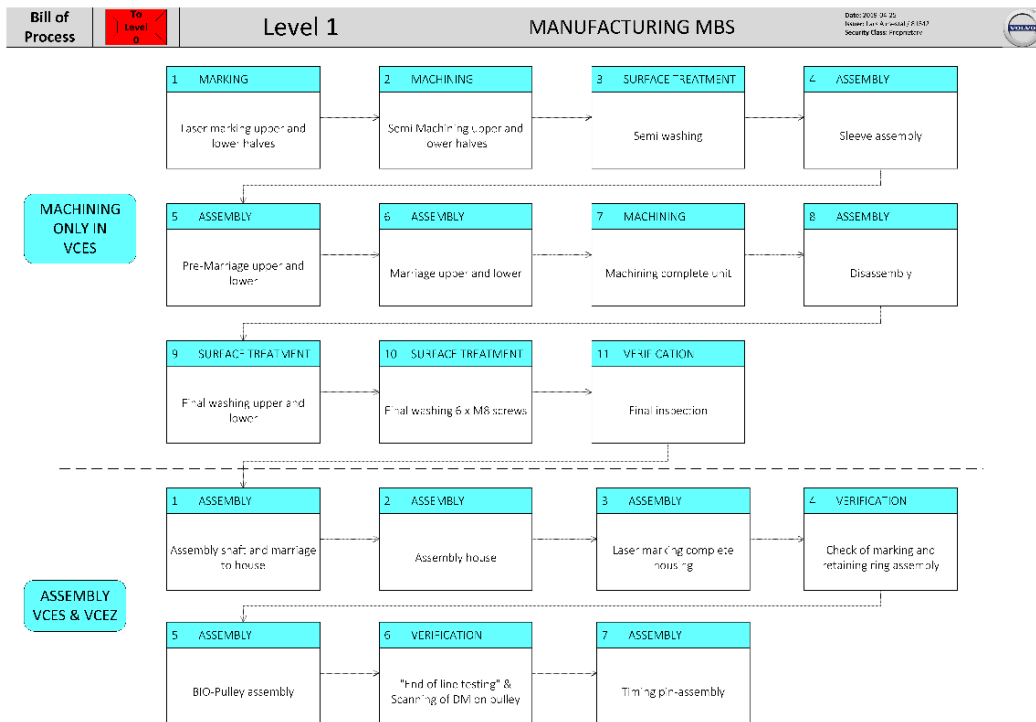


Figure 32: MBS BOP.

In total did 21 persons participate in the survey and the results are interpreted and analysed in the *Analyse and discussion* chapter.

5.3.1.2 Washing

In order to get a deeper understanding about the washing process was Reine Thorstensson interviewed. Thorstensson has long experience within the company concerning the machining processes as both supervisor and more recently, as production engineering. He has been involved in several projects related to the washing process, which implies a good knowledge.

Washing in metal processes is to remove metal shaving carefully before certain steps like finishing and sampling (Thorstensson, 2023). Today there is several washing steps in the process such like a rough wash off/rinse off early in the process and robots wash both with and without lances for advanced washing. Furthermore, does Aurobay use XBC90 as detergent for the washing machines because of it is compatible with the cutting fluid. The compatibility with the cutting fluid makes it possible to send XBC90 through the filters and reuse it. It is a circular flow, and the detergent contain 80-85% cutting fluid. Further on the use of same detergent in all washing machine makes it possible to use same machine for several washing steps. In a more flexible concept, this can support the idea of a universal “washing central”. The high pressure lances that is dedicated for wash certain canals may be a problem but there are good possibilities to run several products in the same washing machine. Figures 34, 35 and 36 below visualise the washing process for CB and CH and process step around the washing procedure. Departments are called “factories”, it is like many small factories under the same roof in the Skövde plant.



Figure 33: A typical washing machine at Aurobay.

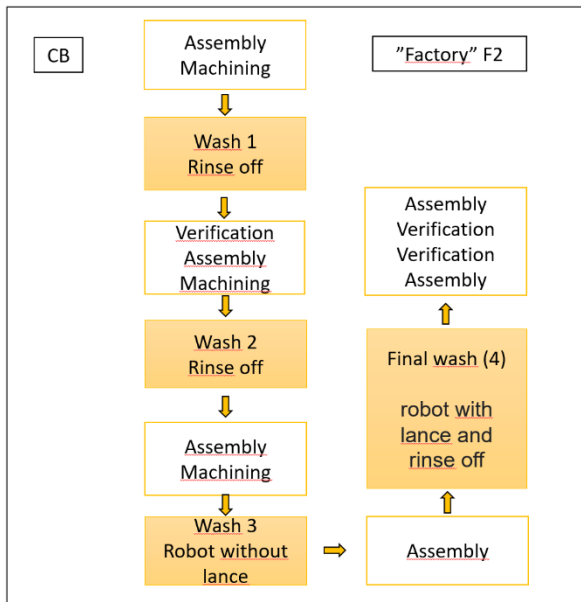


Figure 34: Washing process for CB.

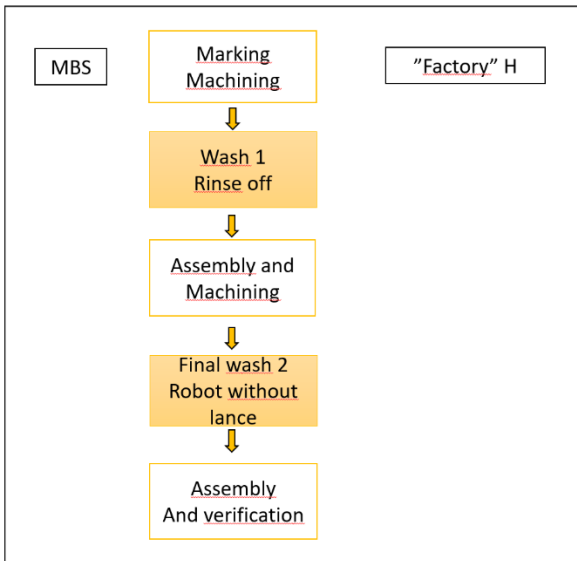


Figure 35: Washing process for MBS.

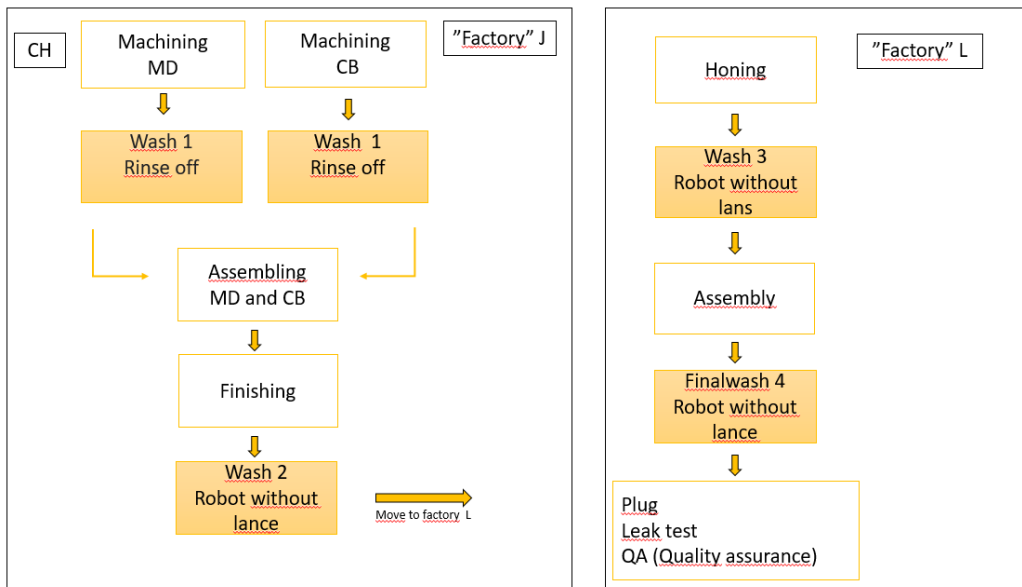


Figure 36: Washing process for CH in the two "factories".

5.3.1.3 Leak test

Upon analysing the bill of process (BOP), the project team discovered that two leak tests were required for CH, while only one was needed for CB. Although one leak test for verifying air leaks appeared reasonable, the need for two tests for CH was not apparent and required further investigation. To gain deeper insights, the project team interviewed Charles Prytz, who works as project support with a broad experience in leak testing and alterations in testing methods between variants and products.

During a leak test, the subject (CH or CB) is tested for defects leaking more than 40 cubic millimetres when subjected to 1.5 bar pressure (Prytz, 2023). To put the size of 40 cubic millimetres in perspective, it is equivalent to the air in a PET bottle measuring one million cubic millimetres. Prytz explains that leak testing involves searching for small numbers related to density, porosity, and substance quality, and there are several methods available,

each with its own advantages and disadvantages. For instance, submerging the subject in water can help identify where the leak is, but it is a time-consuming method. Aurobay, for example, uses a method that is not aimed at verifying an engine and differs from G1 to G3 in that G1 does not search for internal leaks like G3. Petrol and diesel differ slightly in their seal, but the only difference between them.

The reason why CH requires two leak tests is due to its high complexity. The valve seat and valve guide need to be tested with high-pressure oil and water before assembly. Furthermore, the complex structure of CH has even more holes, and adding another test could create more problems than solutions. Prytz uses a metaphor to explain that leak testing CH only once is like trying to plug a water bottle with a thousand holes using your hands. Although it may work, it would be technically challenging to keep all the plugs in place and disassembling the valve seat and guides again to search for the leak would be a difficult task.

Validated the leaking process a step further an interview with quality inspector Frida Söderlund for CH was conducted. Söderlund agreed with Prytz that the diesel and petrol differs and one test instead of two for CH is technical hard (Söderlund, 2023). The first test verifies the oil channels in the cover, and this is necessary before the frost plugs are mounted and holes for hydraulic support are machined for example. Thereafter 20-40 holes more to plug had made the process more complex but from a quality or economy point of view can it be more defensible with one test.

Validated the leaking process a step further an interview with quality inspector Frida Söderlund for CH was conducted. Like Prytz said, Söderlund agreed the diesel and petrol differ in seal and one test instead of two for CH presents technical difficulties leading to quality issues (Söderlund, 2023). The first test verifies the oil channels, and this is necessary before the frost plugs are mounted and holes for hydraulic support are machined for example. Thereafter 20-40 holes more to plug had made the process considerably more complex and influencing quality, but however from an economy point of view can it be more defensible with one test.

To summarise the leak test, the project team discovered that CH required two leak tests, while only one was needed for CB. Charles Prytz explained that leak testing involves searching for small numbers related to density, porosity, and substance quality, and there are several methods available, each with its own advantages and disadvantages. The reason CH requires two leak tests is due to its high complexity and adding another test could create more problems than solutions. The team also interviewed quality inspector Frida Söderlund, who agreed with Prytz that one test instead of two for CH presents technical difficulties leading to quality issues. However, from an economy point of view, it could be more defensible to have one test

5.3.1.4 Quality assurance

To satisfied customer and keep a superior quality, quality assurance by sampling is important. The sampling today of the CB, CH and MBS have similarities but also some differences. An instrument for quality assurance at Aurobay is Quick Statistical process control, a sequential control measuring often called Quick SPC (Sveberg, 2023). This software can be illustrated

like a to do list for the quality check. Quick SPC show you on the screen where and what to check and when you done that, step on a pedal and the program shows next step. This software is pedagogic for new employees, helps to remind you when it gets monotonous and has minimize the risk any parts get through the process. At machining assembling is the primary customer and it is important to check carefully. Today they check 1 out of 60 blocks in each sequence in CB, 1 out of 70 MBS (Andersson P. , 2023) in each sequence meanwhile CH check all machine in one chunk each work shift. 1/60 in each machine makes a sample somewhere in line more than 1/10. At MBS there is also a check each 1/175 plus 1/600 that are more complex. Quality assurance is important and both Sveberg and Andersson stresses the importance of quality assurance in order to find deviations as soon as possible. Engines are expensive and the requirements high, which make sampling important.

Figure 37 presents the final inspection of a CB and in figure 38 there is an inspection of a CH. To get good safety when handling the CH, there are two lifting points when rotating and checking the cam covers/cam cams. If anything on the checklist differs, the object is sent for further scrutiny.



Figure 37: A picture over the quality assurance of a CB. Photo used with permission from Aurobay.



Figure 38: A picture over the quality assurance of CH and cam cover/cam cams. Photo used with permission from Aurobay.

5.3.1.5 Final inspection

As a final step before the engine is going to final assembly at the factory, is a final inspection of the machining is done on each CB, CH, and MBS (Andersson P. , 2023). In case of deviation from a list of checkpoints, the object is subject of further scrutiny. This process is fully manual except ergonomic tools for easy rotating the object and inspecting the surface, search for pores, cracks, and other deviations. As a final step before the engine is going to final assembly at the factory a final inspection of the machining is done on each CB, CH, and MB. This process is fully manual except ergonomic tools for easy rotating the object and inspecting the surface, search for pores, cracks, and other deviations. At figure x there is a final inspection of a CB and at figure y there is an inspection of a CH. To get good safety when handling the CH, there are two lifting points when rotating and checking the cam cover/cam cams. If anything on the checklist differs, the object is sent to another control.

5.3.1.6 Machining the main block and bedplate separately – is it a necessity?

The cylinder block of today consists of the two main parts and are machined both separately and conjoined. The crankshaft is in a later stage in the assembly process placed in between the bedplate and block and creating a strong bolt connection. However, both parts are machined prior to being marriage to each other and due to surfaces, that are of limits after the marriage implies machining separately. Surfaces with limited access are e.g., the bearing seats and some cooling cannels. The Figure 39 displays surfaces in question.

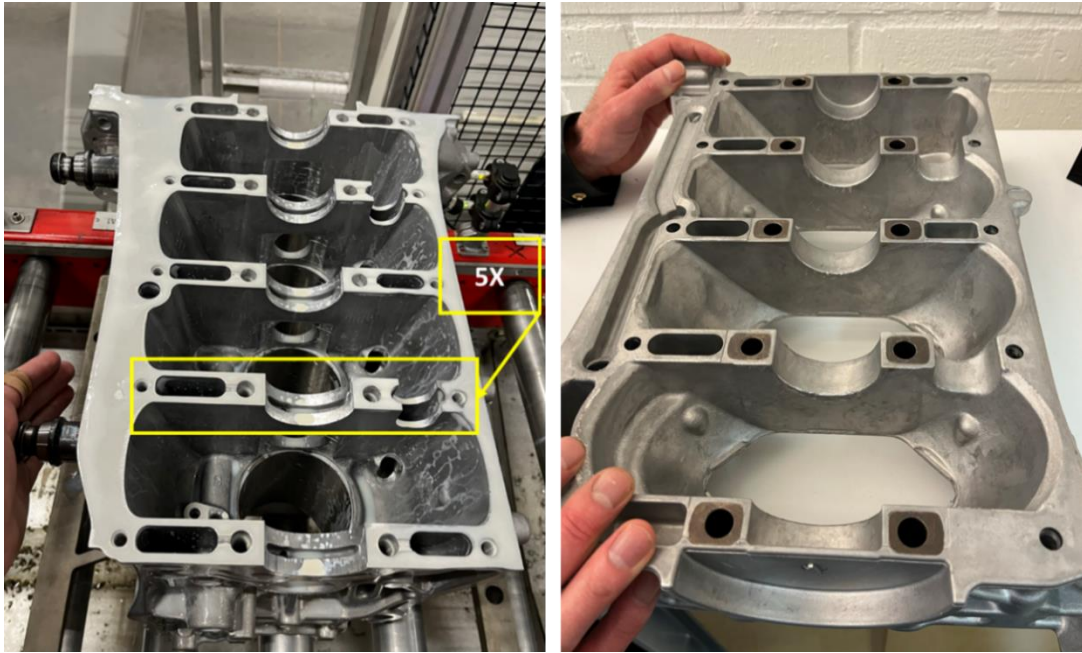


Figure 39: highlighted in yellow is one of the block's bearings seats which holds the crankshaft (not featured) in place together with the bedplate. Photo used with permission from Aurobay.

Additionally, most the block and bedplate be separated prior to leak test (see figure 40) and final inspection, then concealed cooling channels etc. requires to be verified before being sent to base assembly.

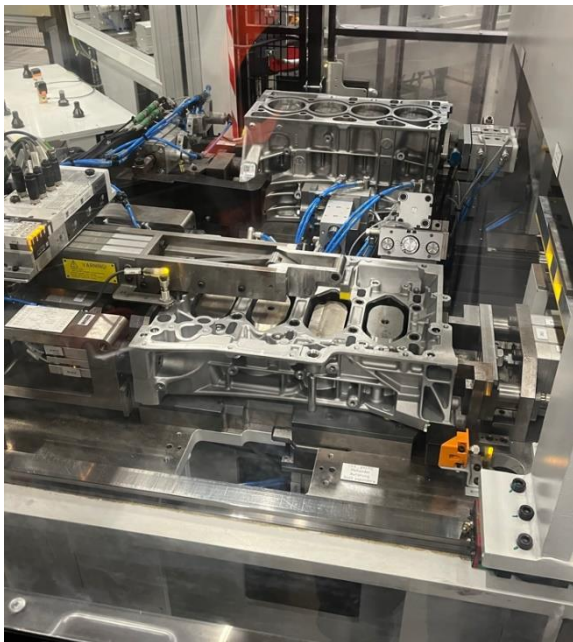


Figure 40: the leak test of cylinder block. Photo used with permission from Aurobay.

5.3.1.7 Construction constraints

The bill of process showed that generation one cylinder block does not use ZPI as fixture system but instead uses a *spot face* fixture system meaning the block is held with force against surface in order to clamp the block. Hence, does a difference between variants of cylinder block exist and further scrutiny revealed that a block with ZPI fixture system is impossible to manufacture in a spot face fixture system (or vice versa). The ZPI system uses grippers that are attached to the object in the beginning of the process and the fixture plate in the machine has sockets for easy docking and undocking (see figure 41). The grippers are reused after the process is complete.

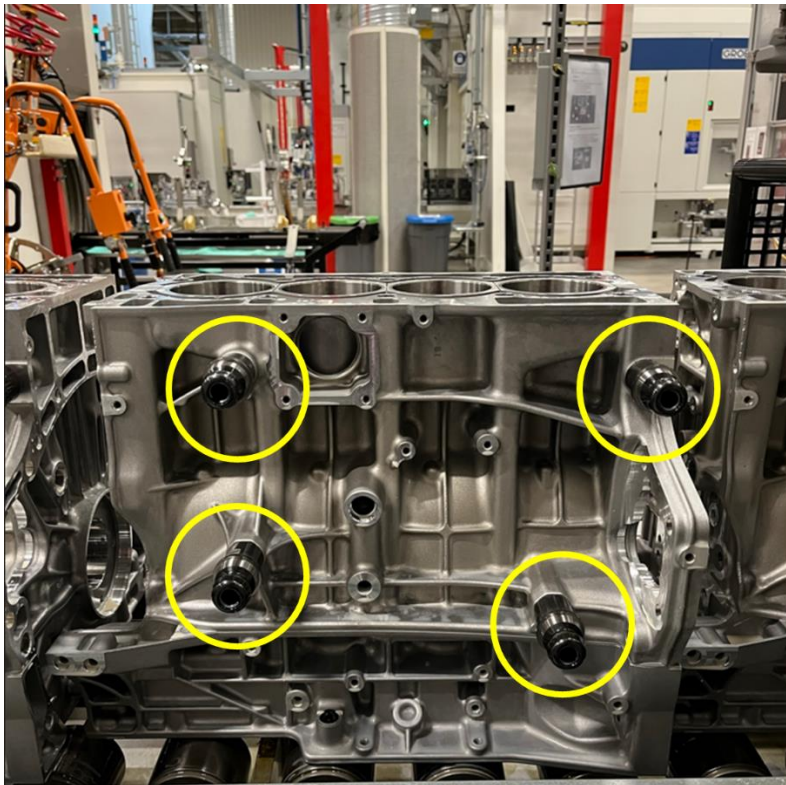


Figure 41: a cylinder block generation three is one product using the ZPI fixture system. The grippers are highlighted in yellow. Photo used with permission from Aurobay.

However, the differences in fixture system have caused headaches before and inquiries trying to solve the issue by implementing ZPI for CB generation one has been made earlier.

According to Lars Johansson, who works with early planning of new products and products flows, did a major investigation look into producing both generation one- (G1) and three (G3) in the same machining line (Johansson, 2023). The main reason was the launch of the generation three VEA engine and at the same time keep the G1 in production. By extending the existing cylinder block production facilities could save money related to installing new production lines and could likewise increase the equipment capability. The reasons to postpone the *end of production* (EOP) of the first VEA engine was the growth in demand for

VEA G1 and with G3 only being launched as mild hybrids (see figure 42). However, further analysis of implementing the ZPI on G1 disclosed that several adjustments to the construction of block, e.g., cooling channels, had to be made to make the system work. The effort and complexity were hastily determined to exceed the benefits and therefore was the decision made to invest in completely new facilities.

Hence, the implementation of ZPI fixture system on G1 was halted due to non-feasible construction adjustments and therefore is not possible to manufacture G1 and G3 in the same production flow but recently have fixture system based ZPI been developed, opening a new potential solution (see chapter 5.3.1.8).

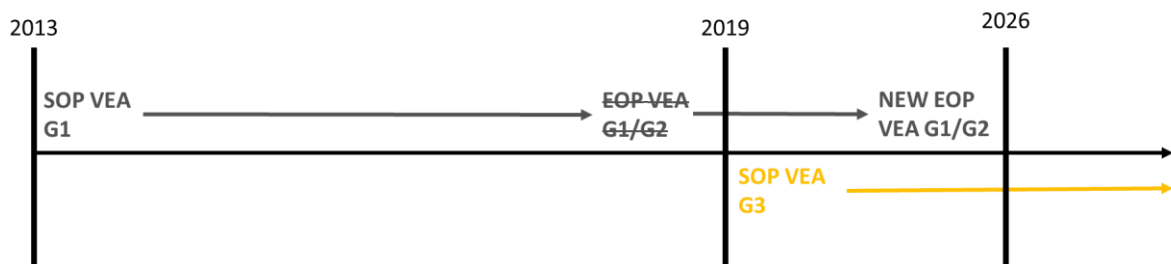


Figure 42: a visualisation of end of production of G1 and start of production of G3.

5.3.1.8 Universal fixture concept

During the process of the construction constraint with the CB did the team meet Jorgen Fock, a Process & Tooling engineer at Aurobay. Fock and his team were working on a universal adapter platform for handling both CH and CB but also having the potential for future products (Fock, 2023). Fock describe the potential of the universal adapter as it can handle multiple different products by adding extensions to the ZPI, who works as a base. It can save time in mix product flow, e.g., manufacturing CB and CH generation three together, but however it might not be necessary if the products already are using ZPI. Fock had some reservations concerning generation one then it would not be optimal in practice but has theoretical chance of working. As discussed earlier, is the generation one CB is using spot face as clamping system instead of the ZPI and the idea is to keep the spot face system in order to avoid constructions adjustments, but however, the universal fixture system requires several different devices often arranged in a cage like manner (see figure 43, 44 and 45).

MBS according to Fock would also work with some settings adjust but the more variables, the harder equation. It is only the construction of the block and head in the equation also number of tools need to be into account.

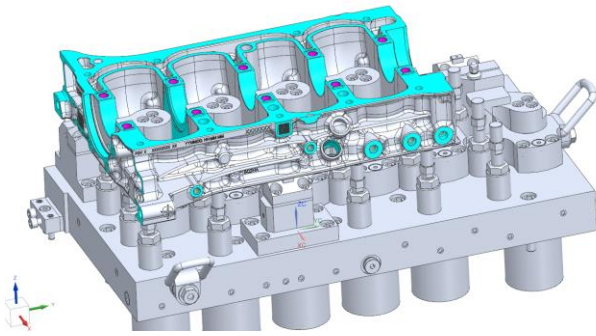


Figure 43: the G1 CB bedplate. With courtesy of Jörgen Fock.

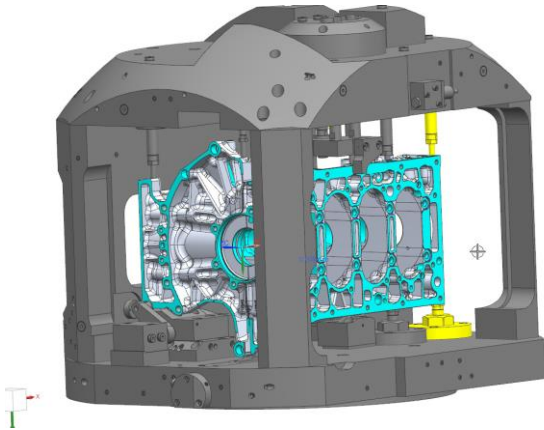


Figure 44: machining the block and bedplate conjoined requires an almost cage like fixture. With courtesy of Jörgen Fock.

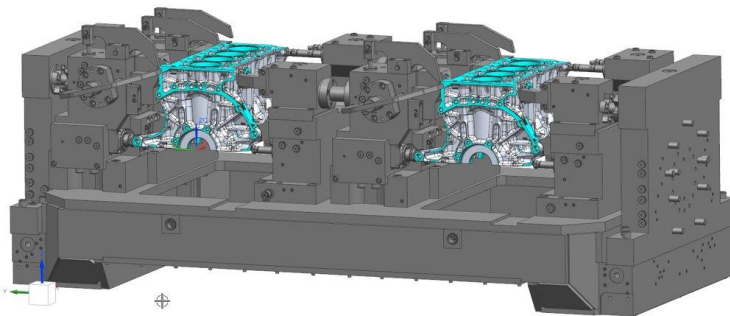


Figure 45: machining of the block only. The lack of ZPI impose a more complex approach to properly clamp the product. With courtesy of Jörgen Fock.

To conclude the interview with Jörgen Fock, the universal fixture concept has big potential handle multiple variants but for the advantages to be greater than the disadvantages, ZPI needs to be present on all objects.

5.3.1.9 Process data and number of machines

In order to test and validate the production concepts were data of processing times collected. The team identified that the *value streams mappings* (VSM) had the data needed for calculating the necessary number of machines, cells etc.

Value stream mapping is a method to sensitive a process and provide an actual picture of the situation (Liker, A Storied History: How Toyota Became the World's Best Manufacturer, 2020). Several VSM have been executed at Aurobay and has become part of the company's procedure of continuous improvement and came in handy when calculating the process time required to complete machining operations. At first is a current state of process mapped and documented by selecting product or a product family, normally starting at the beginning of a large unit e.g., the plant's incoming goods receptions or starting point of the flow and when document and sensitive each individual process step in the current state map. Both material and information flow should be included. After properly and mapping all related steps and activities, could a future state map be developed, and it should entail an adequate road map for *when* and *how* the suggestions should be executed.

Consequently, all relevant data from the value stream maps were concluded and after could the required throughput rate and the average cycle time be calculated as well as the number of machines needed (see figure 46).

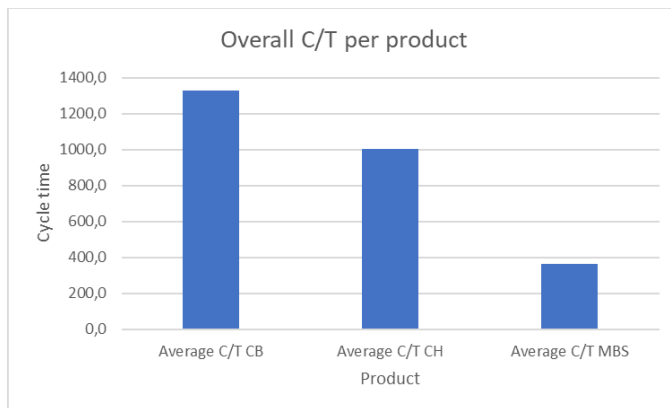


Figure 46: the average overall cycle time per product.

Both the throughput rate and the number of machines were calculated based on the customer demand, which is based on the desired yearly volume, i.e., 10 000 and 30 000 respectively. Takt calculations were based on assumption that the working time per year is approximately 36 weeks or 251 days.

$$\frac{x \text{ units/year}}{y \text{ weeks or } z \text{ days}} = \frac{30000}{36} \equiv \frac{2500}{3} \approx 833 \text{ units/week} = \frac{833}{5} \approx 167 \text{ units/week}$$

$$\frac{x \text{ units/year}}{y \text{ weeks or } z \text{ days}} = \frac{10000}{36} \equiv \frac{2500}{9} \approx 278 \text{ units/week} = \frac{278}{5} \approx 56 \text{ units/week}$$

$$\frac{167}{8,1} \approx 21 \text{ units/h} \approx 0,35 \text{ units/min}$$

$$\frac{56}{8,1} \approx 7 \text{ units/h} \approx 0,12 \text{ enheter/min}$$

The number of machines required for 21 and 7 takt correspondingly are displayed in figure 47, 48 and 49 and are used for simulating the concepts.

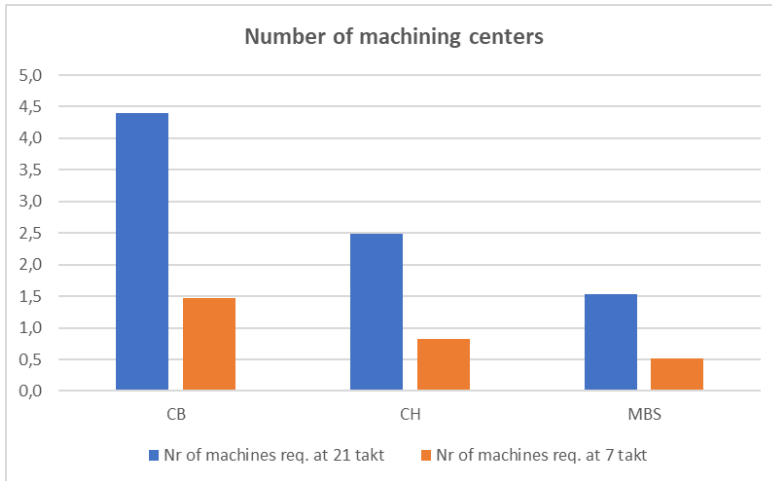


Figure 47: the requisite number of turning machines are considerably higher for 21 takt.

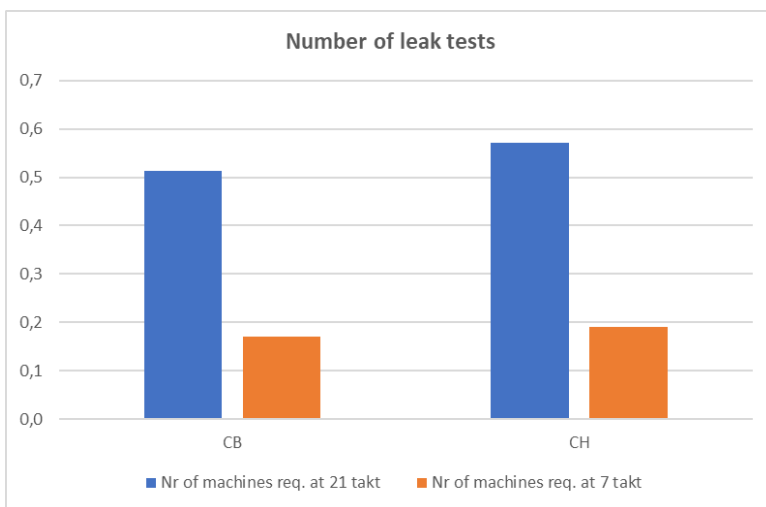


Figure 48: note the number of machines is lower than one for both takts.

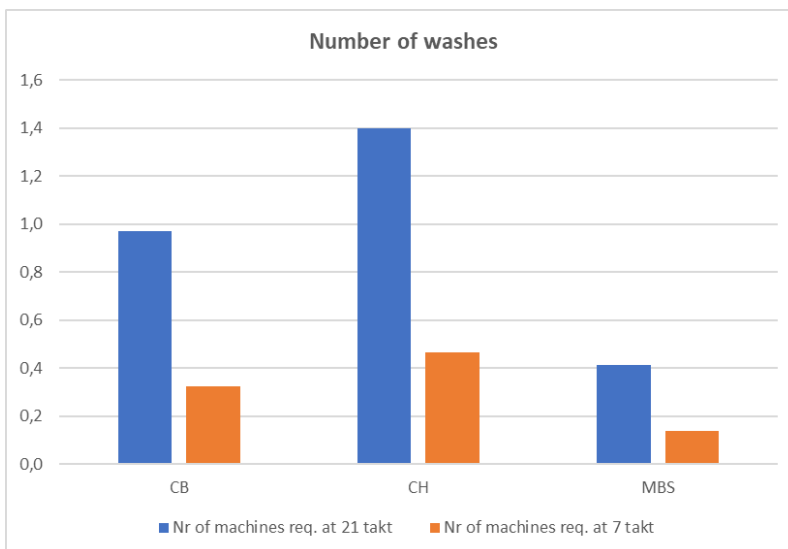


Figure 49: the number of washes required.

5.3.2 From data to concepts

Before generating the suggestions for flexible concepts, the project team visualised the interactions with a fishbone (see figure 50). This was to map how machine related question, the economy behind the concept, input, volume, and general inquiry affects the future concepts and what requires to be achieved. For example, investments can tell how many of the washing machine that need lances and FIFO is one important rule to follow when simulating the concepts.

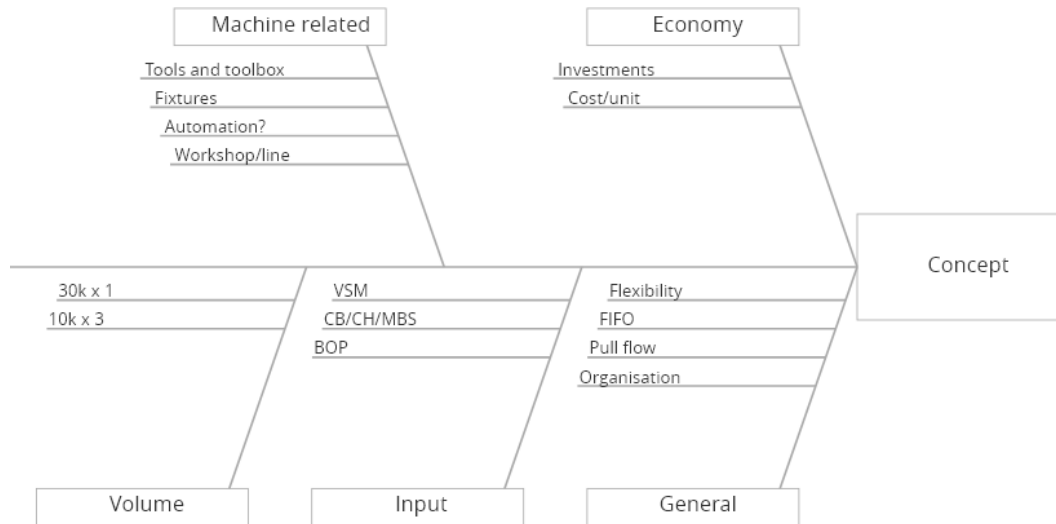


Figure 50: A fishbone visualise data to generate concepts.

6. Analyse and discussion

6.1 Flexibility

6.1.1 Quantitative data – agreement analysis and hypothesis testing – analyse and discussion

The results from the quantitative data collection were analysed in the JMP software. The *Gauge Attribute Chart* and *Agreement Report* displays the agreement within the sample groups and how they compare to each other, as well providing the overall agreement of the e.g., statement or go/no – decision (see figure 51).

Attribute Gauge Gauge Attribute Chart

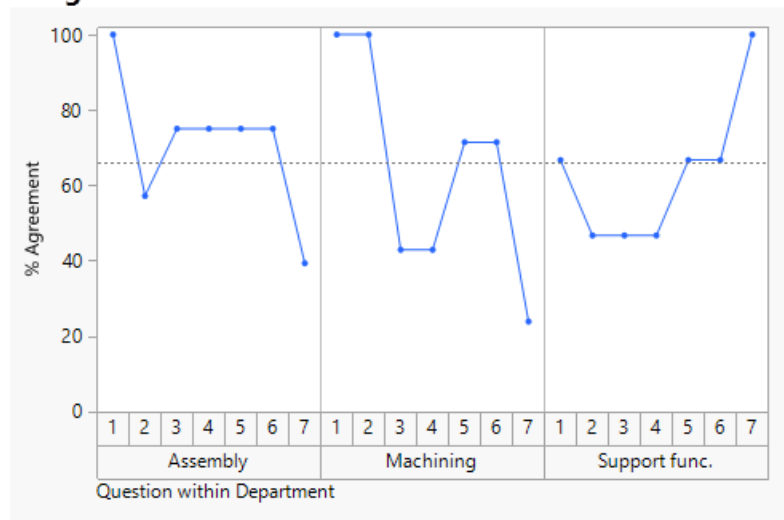


Figure 51: the gauge attribute chart displays the agreement in percent for each sample group.

The analysis of the gauge attribute chart implies that the support function sample group tends to disagree more than the other two groups and likewise overall agreement indicates a rather low agreement between the three groups (see figure 51). However, the assembly department is generally more prone to agree with the statements, which might suggest a difference towards the other group when defining flexibility.

Agreement Report

Rater	% Agreement	95%	
		Lower CI	Upper CI
Answer	66.9643	59.6557	73.5362

Figure 52: the overall agreement is approximately 67 %.

Moreover, the kappa statistics, a measure of non-chance agreement, confirm the generally low agreement across the categories (see figure 51). Kappa values above 0.6 to 0.7 suggests good agreement, values equal to 1 is perfect agreement and if the values are equal or smaller than zero is the agreement only what would be expected by chance or is weaker than

excepted by chance (see table 6) (Feldman, Kappa, 2018). Nevertheless, a low kappa value might also imply, particularly in this instance, that one option or alternative is regarded to not influence flexibility alone and is therefore not selected. Alternative 3 in case seven in the survey states that both alternatives one and two are equally or almost important.

Category	Kappa
Alt 1	0.1219
Alt 2	0.0855
Alt 3	0.6694
No	0.3768
Yes	0.4498
Overall	0.4280

Figure 53: the kappa values vary between 8.55 % to 66.94 %.

Table 6: interpretation of kappa values (Feldman, Kappa, 2018).

<0 No agreement
0 – .20 Slight
.21 – .40 Fair
.41 – .60 Moderate
.61 – .80 Substantial
.81 – 1.0 Perfect

Yet, even if the kappa values across the categories are interpreted *slight* to *suitable* and that a small value the agreement analysis indicates varying results between the sample groups it is not enough to make any definite conclusion.

The deeper analysis consisted of hypothesis testing with help of Chi-square. Chi-square test is highly suitable for when both input and output data is attribute data and establishing a relationship and unions between categorical variables when analysing survey data. However, chi-square is sensitive to small sample sizes and the expected count in each cell must be equal or greater than five (Feldman, Chi Square Test, 2018). Hypothesis testing is applied when trying to minimise the risk of making wrong decision and there are two elementary types of errors. The type I error is when the conclusion is done that the population parameters are different despite they are not and the probability of doing a type I error is associated with α (alpha) risk. Type II error is on the contrary to type I errors that a conclusion is made that the parameters are the same and the probability is called β (beta) risk. The α risk is normally set to 0.05 and the β risk set to 0.10 and thus, the confidence of making the right decision or being able to detect a difference is 0.95 and 0.90 respectively. Normally the α risk compared to the p-value (probability value), which is the signal and noise ratio. When comparing the p-value to the decision criteria (α risk) one can determine if the observed difference is statistically significant or not (Carleton, Hypothesis testing, 2018).

Moreover, the p-value is directly related to if the noll hypothesis can be rejected or not (normally denoted H_0 or H_0). The noll hypothesis is formulated as a statement of no

difference between the initial state and after state and with help of observational data it can be rejected or not (Nationalencyklopedin, 2023). When running a chi-square test the p-value must be greater than chi-square test for the noll hypothesis to be rejected. The team want to prove alternative hypothesis, denoted H_A or H_A , and becomes only true if the H_0 is rejected (Carleton, Hypothesis testing, 2018).

The project team formulated the following questions that the team consider to be important in order to analyse the result from the agreement analysis deeper:

- Is there a significant difference in yes and no answers between the sample groups in total?
- Is there a significant difference in yes and no answers between the sample groups in any of the seven cases?

The noll hypothesis is correspondingly defined:

- There is no statistical difference in yes and no answers between the sample groups in total ($H_0\#1$). Hence,

$$H_0: p_{yes} = p_{no} \Rightarrow H_A: p_{yes} \neq p_{no} \quad \text{there } p \text{ stands for } \textit{proportion}.$$
- There is no statistical difference in any of the seven cases concerning yes and no answers between the sample groups ($H_0\#2$). Hence,

$$H_0: p_{yes\ Q\#n} = p_{no\ Q\#n} \Rightarrow H_A: p_{yes\ Q\#n} \neq p_{no\ Q\#n}$$

there n marks the question/case number.

To illustrate the test the team used mosaic plots to conveniently distinguish and visualise the proportions. Additionally, the contingency table summarises the data behind the plot and reviews the proportions in detail.

The first noll hypothesis was tested with the alpha risk of 0.05 and was analysed in the JMP software and entails two chi-square tests, the Likelihood- and Pearson test, and both tests returned a p-value which was greater than the alpha risk. Hence, the noll hypothesis could not be rejected in favour of the alternative hypothesis. By looking at the mosaic plot (see figure 54) the proportions are visually analysed. The assembly sample group has a larger proportion of answering “no” throughout the survey whereas support function and machining sample group had approximately the same size proportions. Yet, JMP revealed that the expected count in some cells were smaller than five and highlighting the need for additional data. The team decided to proceed without additional data collection since the qualitative data collection is supplementary to the quantitative data retrieved from the interviews and field visit. Hence, the uncertainty is negligible.

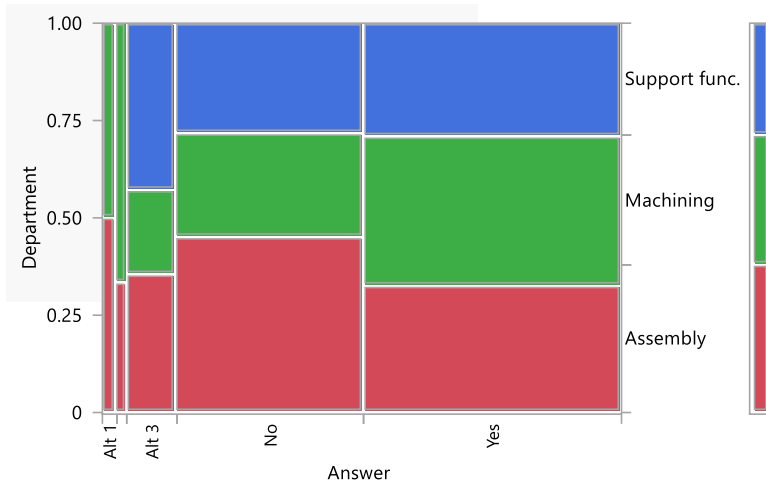


Figure 54: the mosaic plot for H0#1.

The contingency table and test table display the data containing answer response data (see figure 55).

Contingency Table

Answer By Department

Count	Assembly	Machining	Support func.	Total
Alt 1	2	2	0	4
Total %	1.36	1.36	0.00	2.72
Col %	3.57	4.08	0.00	
Row %	50.00	50.00	0.00	
Alt 2	1	2	0	3
Total %	0.68	1.36	0.00	2.04
Col %	1.79	4.08	0.00	
Row %	33.33	66.67	0.00	
Alt 3	5	3	6	14
Total %	3.40	2.04	4.08	9.52
Col %	8.93	6.12	14.29	
Row %	35.71	21.43	42.86	
No	24	14	15	53
Total %	16.33	9.52	10.20	36.05
Col %	42.86	28.57	35.71	
Row %	45.28	26.42	28.30	
Yes	24	28	21	73
Total %	16.33	19.05	14.29	49.66
Col %	42.86	57.14	50.00	
Row %	32.88	38.36	28.77	
Total	56	49	42	147
Total %	38.10	33.33	28.57	

Tests

N	DF	-LogLike	RSquare (U)
147	8	4.6790527	0.0292

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	9.358	0.3130
Pearson	7.673	0.4661

Figure 55: the contingency- and tests table. Please note that JMP has returned to Chi-square test.

Furthermore, the second null hypothesis was tested for each of the seven cases with the alpha risk of 0.05. JMP generated seven mosaics plots and contingency tables in total (see the appendix for all seven). The first case presented to the survey takers was the “perfect state” and all expect one answered “yes” and the both chi-square test returned a p-value greater the alpha risk, thus there was not enough evidence to prove the alternative hypothesis, H_A (see figure 56). However, the null hypothesis could not be rejected in none of the other cases, i.e., there is not enough statistical significance that the sample groups have different perception concerning flexibility.

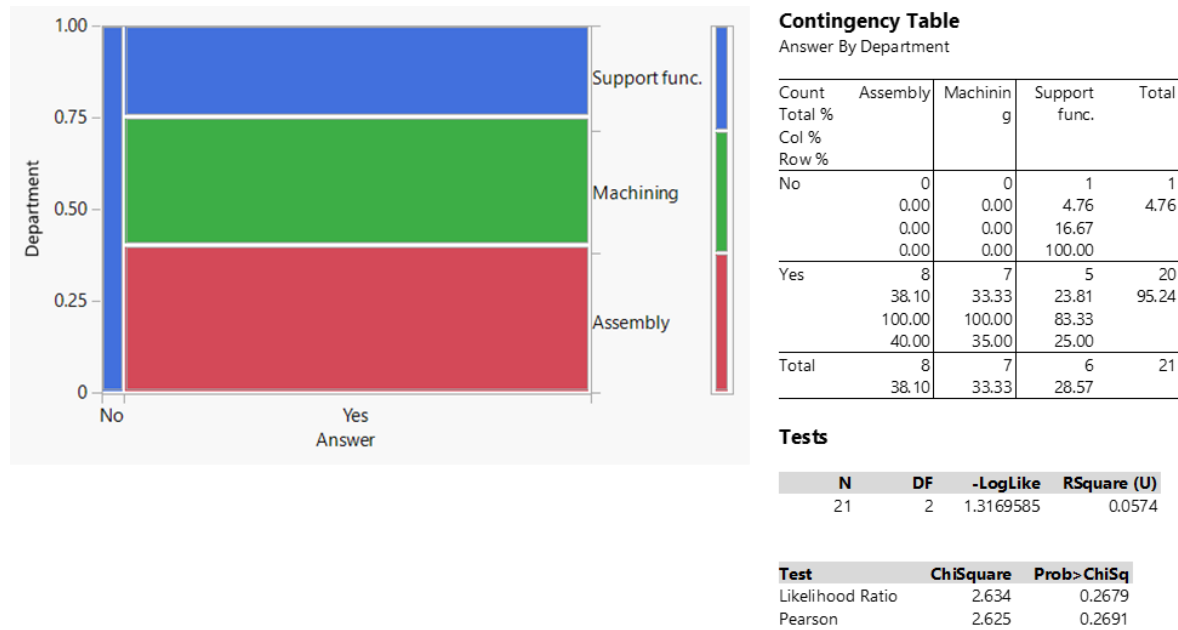
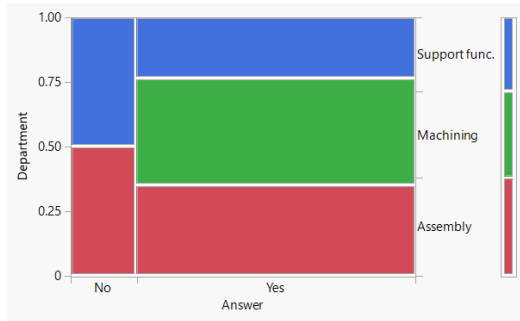


Figure 56: the mosaic plot with contingency table and tests table for cases one.

Additionally, the mosaic plots disclosed that at least either variable volume and ability to manufacture several products must be fulfilled in order for the assembly sample group to consider the flow flexible or not. E.g., in case two training of operators is required but is otherwise the same as case one and regarded to be flexible, but case three is not considered flexible since there are no variable volume but is in other regards equal to case one (see figure 57). Despite having the ability to manufacture variants is not sufficient for the sample group to regard a flow as flexible, i.e., manufacturing Gen 1 and Gen 3-cylinder heads for example as in case four.

**Contingency Analysis of Department By Answer Question=2
Mosaic Plot**



Contingency Table
Answer By Department

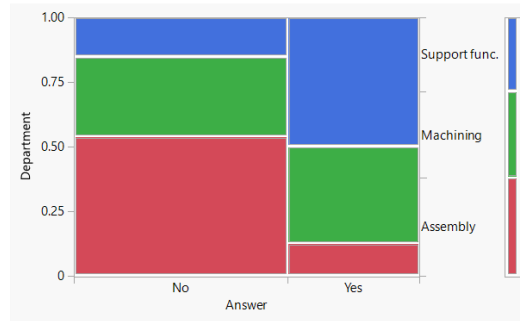
Count	Assembly	Machining	Support func.	Total
Total %				
Col %				
Row %				
No	2 9.52 25.00 50.00	0 0.00 0.00 0.00	2 9.52 33.33 50.00	4 19.05
Yes	6 28.57 75.00 35.29	7 33.33 100.00 41.18	4 19.05 66.67 23.53	17 80.95
Total	8 38.10	7 33.33	6 28.57	21

Tests

N	DF	-LogLike	RSquare (U)
21	2	1.9074007	0.0832

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	3.815	0.1485
Pearson	2.625	0.2691

**Contingency Analysis of Department By Answer Question=3
Mosaic Plot**



Contingency Table
Answer By Department

Count	Assembly	Machining	Support func.	Total
Total %				
Col %				
Row %				
No	7 33.33 87.50 53.85	4 19.05 57.14 30.77	2 9.52 33.33 15.38	13 61.90
Yes	1 4.76 12.50 12.50	3 14.29 42.86 37.50	4 19.05 66.67 50.00	8 38.10
Total	8 38.10	7 33.33	6 28.57	21

Tests

N	DF	-LogLike	RSquare (U)
21	2	2.3414942	0.1021

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	4.683	0.0962
Pearson	4.367	0.1127

Figure 57: the mosaic plot for case two and three with contingencies- and tests tables. Note the difference in yes/no answers between the cases for the assembly group.

Moreover, a similar conclusion can be made concerning the support function and machining sample groups. They are more willing to answer yes if the flow have a combination of at least two of the three stated aspects valid. However, interpreting the mosaic proportions indicates the support function and machining group are more ambiguous compared to assembly, which implies that a different perception exists within the groups.

When all groups were asked if variable volume or multiple variants and products can be produced is more important than the other, a clear majority stated that both was equally important.

In total do the mosaic plots highlights cases number one, two, five and six there most consistency exists between the groups. The groups agrees that variable volume and ability to produce multiple variants and products are important factors for flexibility.

In conclusion neither of the two noll hypothesis can be rejected in favour of the alternative hypothesis, meaning there is not sufficient statical significance to imply that the perception of flexibility differs at the company. However, further scrutiny of mosaic plots implies that despite the lack of evidence of the alternative hypothesis, that the support function- and machining group is to a greater extent ambiguous concerning flexibility. The answers given by the assembly groups are more consistent and the overall agreement of 67 % denotes that in

fact consensus is not true. Despite the ambiguity some important inferences can be made. The inferences are:

- When asked it is equally important for flexibility to have variable volume and ability to produce diverse variants and products. This can be observed at both the kappa values and the mosaic plot for question number seven.
- In most instances both abilities to change volume and manufacturing multiple products must be valid.
- Case one, two, five and six have the greatest uniformity between the sample groups. Number six is the direct opposite of number one.
- Rigid production flows like case number six are regarded to be the least flexible concept.

6.1.2 Visualisation

To graphically display and discuss the data from the analysis phase a fishbone diagram has been created and gives a snapshot of the knowledge and the consensus from this phase. Words written in yellow are the parameters with most consensus in the data collection of define flexibility at Aurobay.

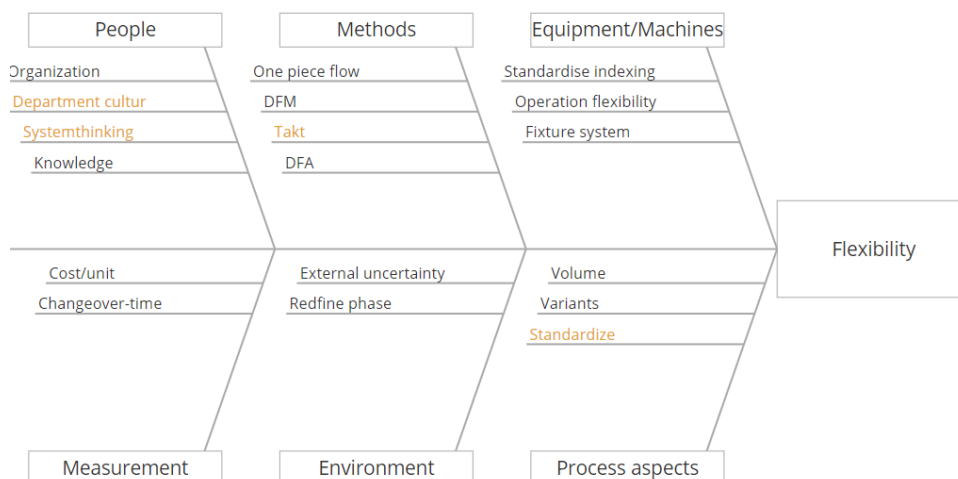


Figure 58: A fishbone diagram visualise the knowledge and consensus at Aurobay.

Department culture: Discussing flexibility during the interviews' indications were made regarding the fact that the term flexibility does not have the same definition or appliance for everyone. During the KAPPA this feeling could be proved. Support function was in general more critical and discussed more around system thinking. This can be caused by department culture but of no statistical significance when all questions were summed up.

System thinking: Flexibility is affected by many things. If the system around is supportive the line itself can be flexible. It is necessary to possibly to scale up/down staffing, have multifunctional machines, good knowledge among employees and understanding of how demand and supply affect the system.

Takt: This is like the system thinking. One takt time cannot change it and it is not flexible. Takt is discussed in the interviews and concepts with fixed takt time in the agreement and

attribute analysis is not seen as flexible. Volvo Tuve moves out its variation and has a fixed tact time, but they have a flexible system due to the parallel flows capable of handling multiple variants.

Standardise: The Interviews can be conducted down to the fact that standardization is the key. Tuve also sees this as important and the concepts in the agreement and attribute analysis do not ask specifically about standardisation. Both abilities to change volume and manufacturing multiple products are equally important which indicates that structure and standard can at least be helpful to success.

6.1.3 Discussion flexibility

The outcome of the analysis is put into perspective and a definition on flexibility and implementation plan is presented for improve flexibility thinking at Aurobay. Yet, the suggested and recommended methodology concerning tools and deliverables for the improve phase is applied by the project team.

The work of generating a flexible concept quickly started to circle about the term flexibility and an improvement of the term seemed necessary before continuing developing a concept that meets the purpose and the given problem statement.

Firstly, to improve flexibility, a broad and a general term was discussed as a starting point as well as some earlier studies on flexibility in production to define and create a background. A background helping the measure phase to be well structured and a good questionnaire about flexible concept. Further on, agreement analysis, hypothesis testing, Kinship Chart and fishbone were used as analysis tools of flexibility and how Aurobay define the term today and the differences and similarities among employees.

After working through these phases, these are the suggested areas of improvement for a better understanding of the term flexible concepts:

1. A definition of flexible concept for use in production.
2. Discussion questions to simplify and clarify communications within a manufacturing context.

6.1.4 Discussion – defining flexibility

Standardisation was detected as one of the roots to good flexibility and systems thinking mindset was another vital part. After reading “Lean flexibility” production concepts need to be flexible when companies are in a phase of redefinition as well as adaption. With the market for electrical engine growing and an uncertain future for the combustion engine, Aurobay is not the only company in a redefinition phase. The whole car engine market is in a redefining phase and flexible concepts need to be organised for scaling up and down with volume and workforce. Department thinking is easily happening and a well-structured concept with good standards can make it easier to manage new management and different cultures.

Further on, flexibility is broad and depending on topic it can mean different things and factors do not weight the same in every situation. To get a common picture and consensus is it

critical with communication and remove and reduce risk for miss understanding. In production flexibility is a common topic and when talking about developing flexible concepts, some things need to be clarified. First, what is prioritized in this situation? What is the purpose and considered as good? Secondly, how will this change affect the value chain? Thirdly, standardisation is a root cause of flexibility and should be discussed in the context of flexible concepts generating.

These are three suggestions to go through when discussing and developing the flexible production concepts:

1. What is prioritised?
 - a. Is it Volume? Think of the quantity of machines and bottle necks.
 - b. Is it Variants? Think of Heijunka, multifunctional tools and move out variation that cannot be standardised in parallel and supportive flows.
 - c. Workforce? Flexible schedule and simplified learning.
 - d. Product X? Multifunctional tools, installation and competence among employees.
2. Can good flexibility here make flexibility worse somewhere in the value chain? Can this contribute to suboptimization instead of flexible system for us?
3. How can it be standardised for long-lasting flexibility?

During a discussion of flexible concepts, the definition of what is flexibility is not subject of total unanimity, and a clear definition must be created. This is the result of defining the flexible production concept.

The definition of flexible production concept is:

A flexible concept is well standardised and the people and machines within and around the concept are organised for handling variation in volume and products. Machines are likewise capable of manufacturing multiple variants and products. The concept is ready for adaption as well as redefinition of new strategies for meeting the market demand. Flexible concepts are built with a system thinking and can handle change in culture, workforce and management.

6.1.5 Implementation plan

To easier implement the flexibility definition and discussion questions for flexible concepts has an implementation plan been formed (see table 7). This is a suggestion of how implementation can look like and the output of this process.

Table 7: Table telling step, tools and outputs for flexibility in the Control Phase.

Step	Tools	Outputs
Effective flexible discussion	Discussion and one page guide	Better communication
Define flexible concept	Meetings, one page guide and DEFINITIONS at intranet	An agreed picture of flexibility

The first implementation is the discussion question shaped in this thesis work. The project team suggests discussing the proposed questions. This is because questions 1-3 above may need to be redesigned for understanding and suited better for Aurobay and the learning process at the company. After this discussion, everyone has more insights, included, and have a common ground to further on discuss flexible concepts. The question is broad and need to be more linked to the context and fit into the routine instead of a must that fells like pious from nowhere. This may be about flexibility, but it is also in general easy to make errors in the communication and today there are slightly different views of the term flexibility among different departments, and the project team sees a need of these questions.

Secondly, how to implement the definition of flexible in production concepts? This definition can simplest be spread verbally and on the intranet. After this report is done and Aurobay continues with the concepts from this thesis work this definition of flexibility are the intended starting point to understand the concepts and flexibility. Therefore, a document called “Flexibility-one page guide” and adding this definition into DEFINITIONS at the Aurobay’s intranet the term is easy to access and the risk it gets lost is reduced. By-including a big sample size, the project team hopes the term is created by and for the customer of this thesis work. Through interviews, meetings and discussion around this topic during five months the project team thought the implementation phase had already started. This definition is meant to make it easier to verify, understand and measure flexible concepts.

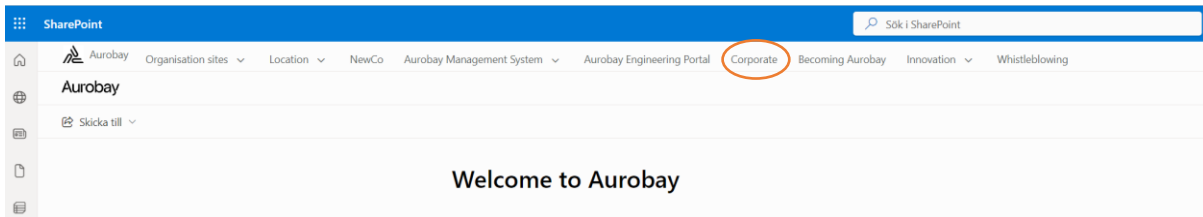
6.1.6 Flexibility – Control phase

Last step in the method of DMAIC is the control phase. The control phase is about getting the improvement to stick and sustain, which in this case are the flexibility insights. A successful control phase provides a long-term effect and lasting control of a DMAIC project (Carleton, Control phase, 2018). This solution for control is only suggestion for starting point and best control needs to be maintained internally.

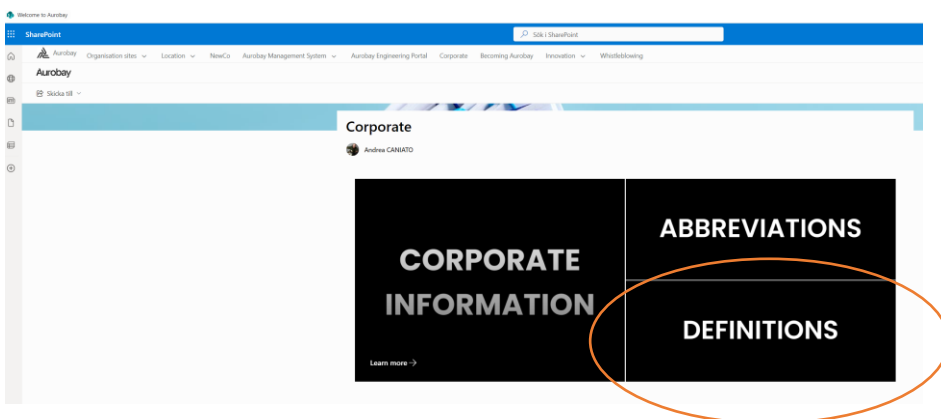
For control it is important to keep it simple and therefore the term flexible production concept can be added to Aurobay’s definitions. The figures below are step by step where to find definitions at the company. This is to get the definition of flexibility simultaneously with

other important terms to be yearly be updated and refreshed. There is a lot of information around us daily and using the intranet that already exists as a platform is a good place to use. In the process of making good searchability at the intranet this definition as a *one-page guide* together with the discussion questions. Without this *one-page guide*, this will greatly depend on the verbal communication and people that have been or will be in contact with this thesis work. Through having a big quantity of interviews and working closely with employees during the process hopefully the term will be glued both written and verbally.

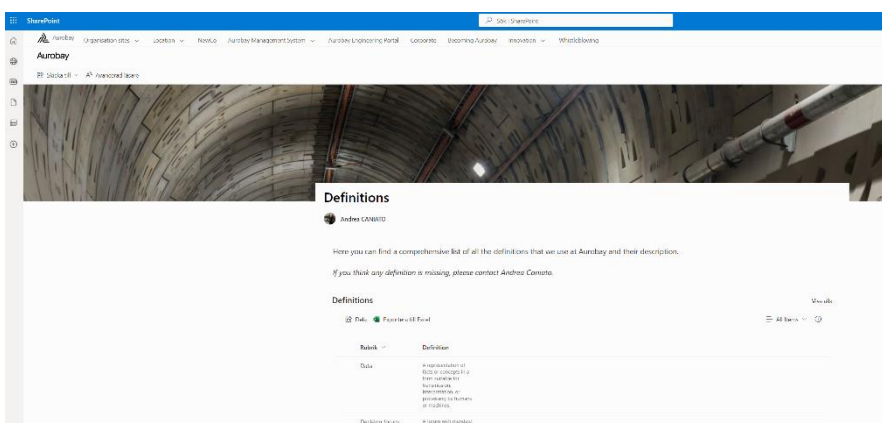
1. Go to the intranet and click on *Corporate*



2. Click on *DEFINITIONS*



3. Scroll to *Flexible production concepts*



6.1.7 Benefits and risks

Definition and discussion questions are abstract and cannot be followed up with regular samples and put into a control chart as unit of engines or availability time in a machine. There is a risk when you cannot quantify it and follow up in automated way like a computer collecting data and then you can on a regular basis analyse the output. Still nothing will change only because a chart was created (Carleton, Control phase, 2018). Benefits with something abstract is that it can be easier with adaptation. There is also no prior knowledge needed to understand and discuss the topic. A *one-page guide* is an important step towards understanding, and if flexibility continues to be an important topic it will be accessible from the intranet by everyone, and worth-by month should not be underestimated.

Through including above 20 persons in this discussion about flexibility at Aurobay and Chalmers, making a *one-page guide* at the intranet and publish this thesis work, the knowledge can be long lasting and support dialogue and work about flexibility in production.

6.2 Production concepts

In this chapter is the process from building, discuss, simulate, analyses and discussion of production concept and belonging context such as investment and general principal.

6.2.1 Investment

The three different concepts have different investment costs depending on the number of machines needed and cashflow related to the material cost for each product. A comparison between the projects three concepts and two of the existing production lines at Aurobay has been made. Both the cost for purchase completely new machines and reusing quality assurance and mills machines have been used as inputs. These can be reused for sustainability reasons (both economic and ecological).

The calculation is made in million Swedish crowns (MSEK), 30 000 units and the discount rate are compared to Stockholm OMX 30 that is roughly 8,5% last 30 years. To visualise the comparison of different concepts easily, has a colour coded table been done (See table 8 and 9). The comparison down below is in relative terms with 10 as starting point. Red implies worse than the starting point and green indicates better performance. It is a scale of seven with three red, three green and one white. For example, is 6 approximately 4 better than starting point of 10.

Table 8: Comparison of Investment cost for the concepts.

	Concept 1 new machines	Concept 1 old machines	Concept 2 new machine	Concept 2 old machine	Concept 3 new machine	Concept 3 old machine
Investment cost	13	8,3	10	6	8	4,4
Payback time (year)	17	11	10	6	8,3	4,3
Net present value	Negative	Negative	Negative	Negative	Negative	Positive

Another comparison approximates the investment cost for producing these low volumes in already installed production lines. A comparison between buying a new set up of machine or reusing all machines.

Table 9: Comparison of investment cost for new production concept in today production line.

	CH gen 1 today new machine	CH gen 1 today old machine	CB gen 3 today new machine	CB gen 3 old machine
Investment cost	25	5,5	13	7
Payback time (year)	25	10,6	17	9
Net present value	Negative	Positive	Negative	Negative

To conclude the investment calculations, it is a high payback time to buy a new set-up of machines longer and therefore a big risk of not earning money on the investment. The automotive industry is changing and will do so for the next couple of years and a payback above 5-10 years might impose problems if new investments are required. If reusing machines instead, the payback time is significant lower and with lot of machines already installed in the factory, are adjustments possibilities of them reasonable.

6.2.2 Building the concepts

The data input from the BOP and VSM were used to generate and calculate concepts (see chapter *Mapping and understanding the product similarities and constraints*). One concept contains three dedicated lines for manufacturing of CB, CH, and MBS with a yearly volume of 10 000 units each. The second concept focus on having flexibility of producing three variants with a yearly volume of 30 000 units, there proportions are evenly distributed on the products.

Moreover, a third concept was also created since the team identified constraints concerning the generation one cylinder block and that other variants and products had a greater combability of being produced together. Additionally, by removing cylinder block generation one from the concept can the manufacturing of the other variants be more standardised.

Therefore, the idea of this concept produces cylinder block gen 3 and cylinder head gen 1+3 together.

After the measure phase a job-shop inspired concept could give the flexibility needed for future concepts. There are differences between generation one and three as well as between the ingoing products. As discussed previously were machining operations executed in high volume dedicated flows, suitable for continuous flow and the cash flow from high volumes can justify machines only performing certain operation tasks. However, with 10 000 to 30 000 in yearly volume, there is going to be too much no value adding time, tools, machines, and workforce implying losses and low equipment utilisation implying an alternative production approach.

As defined earlier, to be flexible is the production concept need, capability of handling several changing factors within and around the production line, e.g., products and variants, and be ready for new demand. Findings presented in this thesis work highlights that standardisation is important to be successful when designing and maintaining a flexible concept. At this conceptual level are new ideas and new perspective the focus but however a plan for standardisation (DFM) needs to be included when proceeding with flexible concepts presented and meet the demand of tomorrow.

6.2.2.1 General principles for concepts and assumptions

When designing the production concepts are 13 principles followed. The principles frame the concepts and provide an overall uniformity to them.

- The concepts follow Aurobay' s pull flow and will not send in an object into production or further in line without demand from customer. However, the lines are arranged in a job-shop layout, but the principle of continuous flow is applied.
- All the concepts follow the principle of first in first out (FIFO) as in earlier production.
- The concepts and the working methods should be standardised.
- The ratio of the boxes in the figures is not tested.
- Manually loading and unloading instead of gantry loaders.
- Automated assembly operations.
- Loading of the machine is executed manually and not by gantry loaders, typically in use today (insert picture). By manual handling of material, the desired flexibility could be achieved with smaller investments expenses.
- No disturbances in the logistics with material to and from the concept.
- The fixture plate can handle all different fixture systems.
- New machines are purchased with adequate capacity to store all necessary tools. If machines are reused, are measures taken to secure the tool capacity.
- Availability has been tested from 80 up to 99%, see appendix for more details.
- The Mean down time are two minutes.
- The developed definition of flexibility is considered.

6.2.2.2 Framing the concept

In this section the general principles are explained more in depth.

6.2.2.2.1 Why combining job-shop, continuous flow and pull thinking?

The production philosophies of job-shop and TPS, i.e., heijunka, jidoka, pull- and continuous flow principle, have indisputable advantages, discussed and identified in the literature studies chapter. Despite the job-shop layout having great flexibility concerning the ability to handle a wide range of products in significant quantities, were the less favourable features of complex production planning, prolonged processing- and lead times, extensive set up times and unevenness in equipment utilisation also identified. With longer lead times is the tied-up capital in form of WIP and production material increased, implying more buffers and problems detecting quality deviations. Yet, continuous flow generally requires more machines since they are lined-up in a sequence and with less buffers will disturbances cause more stops. The time to remedy quality deviations and causes of disturbances will probably be shorter since they surface earlier. Push systems tends to overflow the market with goods, leaving the sales department in an uphill battle trying to get it sold. Moreover, should heijunka (levelling) be applied since persistent work will lead to minimising the three M's (waste, unevenness and overburden). Additionally should jidoka be applied to flourish quality work. For a complete review of the production philosophies, please the literature studies chapter.

Since no production philosophy is complete or flawless could a combination of them present the possibility of exploiting their strong side and minimising their less positive characteristics. By arranging the machines and cells in a job-shop layout would add the flexibility of e.g., going from machine A to B or C depending on which of them that is free, and applying pull thinking instead of push will decrease the WIP since orders only are created when demand exist. Besides, shorter lead times implies greater flexibility to customer demands then the time from order to delivery is shorter creating the possibility of optimising WIP and other process parameters. Moreover, quality will likely be improved and non-value adding time will be reduced by deliberately removing and decrease in number of buffers forcing non wanted phenomes to the surface. The unevenness of equipment utilisation might be harder to mitigate.

Hence, by combining the job-shop layout with continuous flow, heijunka, jidoka and pull thinking could the desired flexibility be meet without long lead times, giant buffers, lurking wastes and quality issues be achieved.

6.2.2.2 Automation – to what extent?

According to Jeffery Liker (please see the literature studies chapter) shall automation be regarded as a tool and not a solution. In many eyes automation is equal to efficient processes, however high investment cost and more rigid installation mostly decreases flexibility. The Volvo Tuve plant has for instance a few completely automated cells in order to avoid build processes not up for rapid changeovers due to variants and product changes. Liker refers to

the Tesla plant in Fremont, there Tesla tried to automate the final assembly which ended in a too complex and unsolvable puzzle. Moreover, automated cells are good at performing repetitive tasks offering a more levelled quality compared to if the same tasks were made manually.

Holweg et.al highlight the potential of reducing the unit cost since less operator interference is required but adds the automation in a production line, will increase the degree of dedicated equipment only capable of handling some tasks and products and hence reducing the flexibility. Also highlighted by Holweg et.al is the complexity challenge, referring to automation could in some circumstances lead to undesired system complexity.

Today are loading and unloading for material in the machining line executed through automated gantry loaders providing shorter lead times and unit cost reduction and is suitable when production rates are high. Nevertheless, the system of gantry loaders is an example of a rigid and dedicated installation but in a job-shop layout commonly used for lower production volumes and greater product variety, would the payback time for a gantry loader system be too long and possibly adding unwanted complexity to the system.

Yet, a feasible area for applying automation is the assembly related to machining, e.g., assembly and disassembly of block. Industrial robots can normally execute a wide range of tasks depending on the tool or tools at hand and planned well lower the cost per unit as well as improving ergonomics, becoming an enabler in the production process.

Thus, loading and unloading of material shall be executed manually to increase flexibility but assembly tasks shall be automated in order to avoid unnecessary system complexity.

6.2.3 Concepts

For concept one with three times 10 000 there will be a requirement to purchase three unique sets of machines. The three sets are presented below and shown in figures 59, 60 and 61.

MBS:

- Machining
- Washing
- Assembling
- QA

Cylinder head:

- Machining
- Washing
- Assembling
- QA
- Leak test

Cylinder block:

- Machining

- Washing
- Assembling
- QA
- Leak test
- Classification
- Main bearing
- Honing

The cells should be arranged with the cell with longest cycle time in the middle and cells with shorter lead times in the outer perimeter, and in sequence according to the BOP implying wastes such as waiting, unnecessary transportation etc. could be reduced.

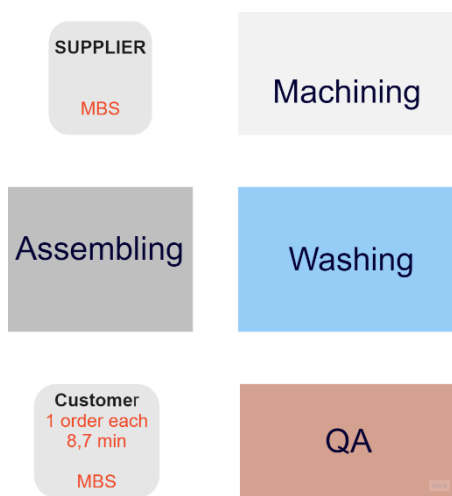


Figure 59: MBS line.

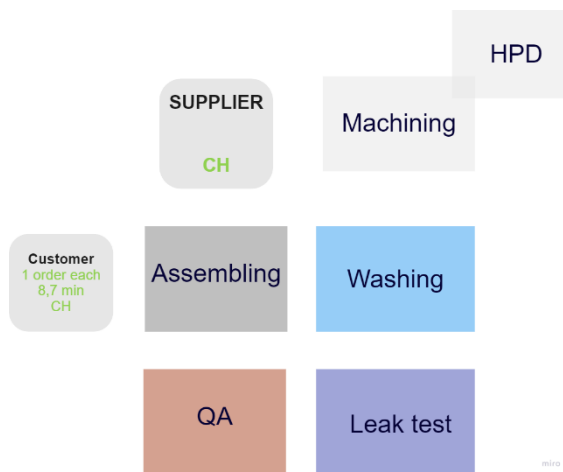


Figure 60: CH line with 10 000 units in yearly capacity.



Figure 61: CB line with 10 000 units in yearly capacity.

The CB line requires two machines for managing 10 000 CB according to the VSM calculation. In the concepts the washing machine are placed in middle like a washing central. Machining has the longest cycle time and washing the object quickly before continuing machining is important. QA, leak test and classification has a lower occupation rate and are therefore placed in the perimeter.

In the BOP there is step by step but in figure x, y, and z the cells in concepts of these three are visualize. The process starts and ends with marking/register the object and therefore the supplier of material is located close to the assembling cell.

The second idea is to produce the 30 000 units in one concept (see Figure 62). Assembly, washing, and machining happen multiple times and is central for the concept to smooth. Depending on cost for tools some machine will focus on the rough processing and other on finishing. The plan is this job-shop inspired concept will take the object forward as a line production and have multiple machines on the side and be ready for outer assembling on the other side.

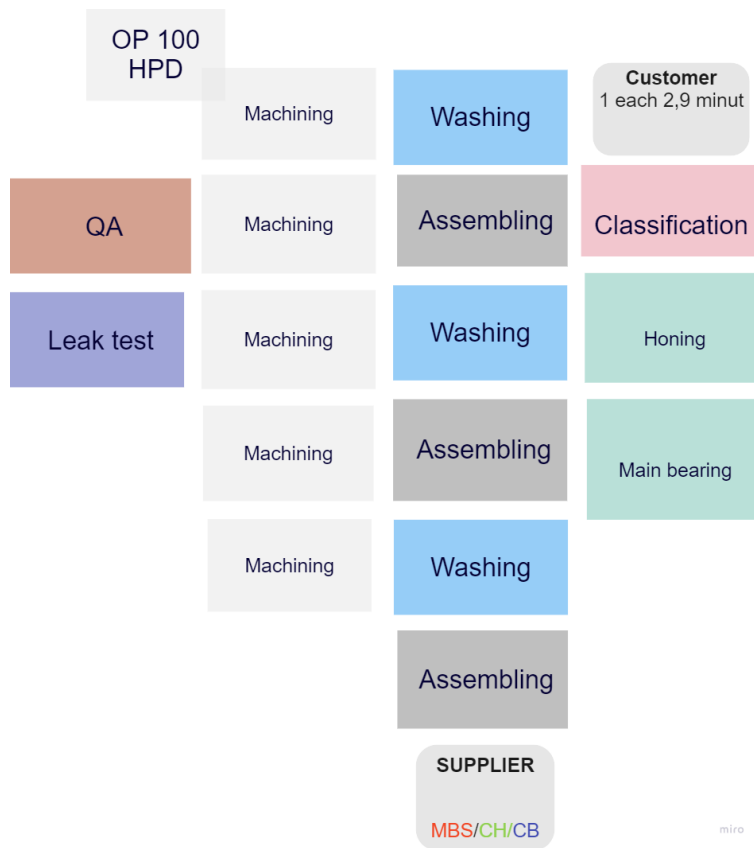


Figure 62: Concept for produce 10 000 MBS, 10 000 CH and 10 000 CB.

One way to standardise the processes at Aurobay is by the zero-point index. This gives the object same grip and less turn over time in the flow. This index is used at all generation 2 and 3 an also works for CH generation 1. Though to the construction constraints of CB generation 1 it is not possible now for this object. By exclude it, the concept has better possibility to be optimize for the other variants. In this concept the washing machine still work as a washing central and four machines according to the BOP gives enough capacity.

Besides from only simulating the concepts asked of the customer, was a third concept simulated and analysed. The third concept builds solely on the idea that only products with ZPI index should be included in the concept, i.e., not CB G1, since the CB G1 utilises the spot face fixture (see figure 63 for concept three).

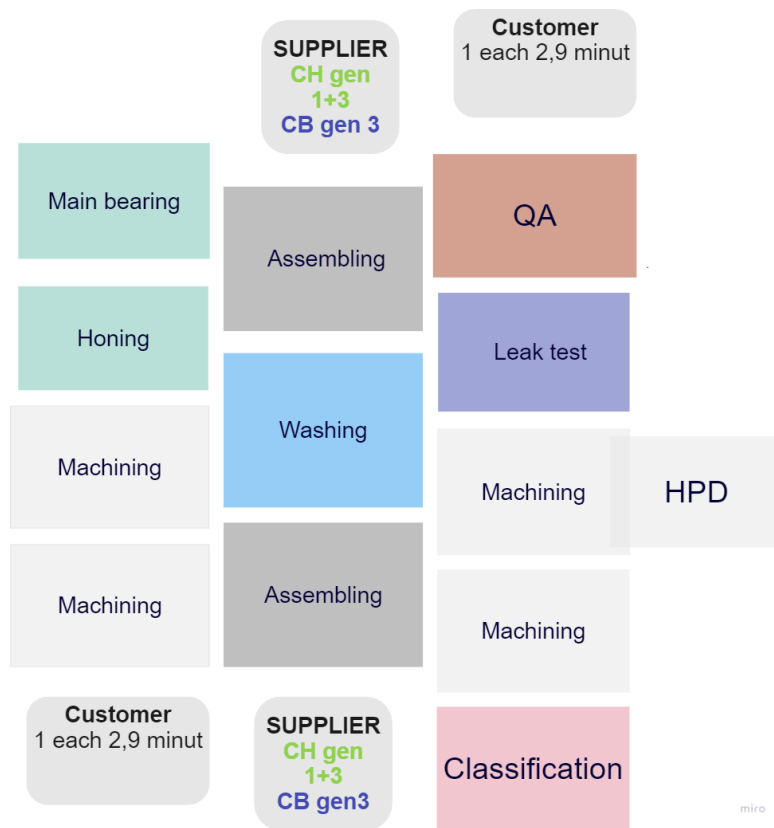


Figure 63: Concept for produce CH gen 1+3 and CB gen3.

6.2.4 Simulation of concepts

The simulations in this thesis work have been created in Siemens *Plant Simulation*, normally referred to as *Plant sim*. The software enables simulation, visualisation, analysis, testing and optimisation of the production concepts (Siemens, 2023). Plant Sim models are used to optimise throughput, relieve bottlenecks, and minimize work-in-process. The simulation models can take handle internal and external supply chains, production resources and business processes and therefore allowing to analyse the impact of different production variations. The in-plant simulation can generate extensive statistics and charts to support dynamic analysis of performance parameters, including line workload, breakdowns, idle and repair time, mean time to repair and so on. Likewise proprietary key performance factors are possible for the program to generate. For these concepts the simulation is kept on a basic level and use a more holistic approach than more detailed.

The team turned simulation engineer Erik Birgersson who works at the manufacturing engineering department, more specifically Global Line & Equipment, to simulate the concepts. Birgersson has a BSc degree in production engineering and have good knowledge within the field. These concepts in plant simulation have been simulated by the Simulation Engineer Erik Birgersson at Aurobay Global Line & Equipment. A fantastic support for testing and develop our concept ideas. The project team thanks Birgersson and his engagement in theses simulations.

6.2.4.1 Input to the concepts

To get the concept from fishbones, whiteboards, data sheets in excel to a simulation model, two meetings were held with Birgersson. Firstly, the team presented the project teams ideas, goal, and thoughts. During the meeting we discussed what input that was necessary to achieve the set-up goals and find a balance between detailed simulation and an easier model. Agreeing on a desired output, Birgersson set up an Excel sheet with the necessary input and during the second meeting he presented this sheet for the project team. After this meeting has new concept data continuously been added and step by step improved and analyse the simulation results. The input for the concepts included:

- Variants like CB gen 1 petrol and CH gen 3 diesel and MBS etc.
- Machine name for each cell.
- Operation number for each indivial process steps.
- How to prioritise different variants? First in first out methodology (FIFO) was applied.
- Cycle times
- Description of what each cell should perform
- The throughput is either 7 or 21.

For more detailed input see appendix.

6.2.5 Analysing simulation outcome

Key parameters for analysing the simulation outcome were identified as *Jobs per Hour (JPH)*, *availability* and *Work in Progress (WIP)*. The JPH measures the systems throughput and when observing the JPH results from the simulation for the different production lines, can the systems capability of deliver customer demand be studied and compared to each other. Moreover, the JPH should also be compared to the WIP since an optimum between them can be discovered, meaning the lowest most feasible WIP could be disclosed. Low WIP implies that a better ratio for the tied-up capital in line as well as adequate throughput. Availability is a metric of how much of the time the equipment is useable for production operations.

Table 10: the activity in each cell.

Cell 1	ZPI, RFID and assembly
Cell 2	Machining
Cell 3	Washing
Cell 4	Leak test
Cell 5	Classification
Cell 6	Main bearing
Cell 7	Honing
QA	QA

6.2.4.1 Concept one – three dedicated lines

The outcome from the simulation were interpreted in Excel and visualised in diagrams and graphs and first in concept one was the JPH output compared towards an increasing WIP. JPH most equal to seven in order to deliver the customer demand. This is because this concept is divided into three lines and JPH for the project is 21.

Several simulations runs were performed and an optimum between the JPH and WIP was disclosed to be when WIP = 4 and is valid for all three products (see figure 64). Trails with higher WIP did not influence the throughput and thus only affecting the tied-up capital in a negative manner. After exceeding 8 in WIP the models get blocked for CH and is unable to function (see figure 64). The same behavior occurs at WIP 14 respectively 20 for CB and MBS.

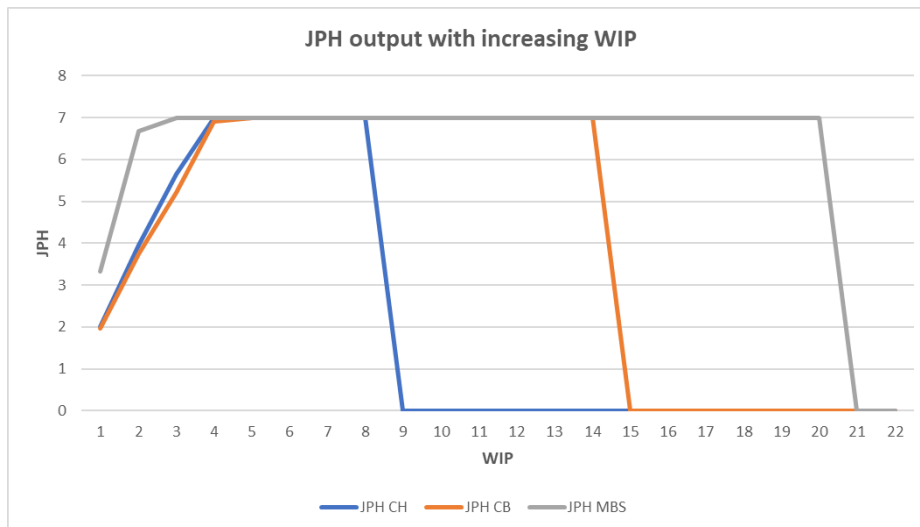


Figure 64: JPH output with increasing WIP.

By analyse utilisation rate of machines in concept one, the highest is achieved at WIP 6 for all three products. Looking at each specific machine cells, cell two with machining occupied the most at 74% for CH followed by 74% for CB and 22% for MBS. The overall utilization ratio is low, implying a greater amount of non-value-adding time (see figure 65, 66 and 67).

However, if you add set-time the utilisation rate will rise all products but this is still no value-adding time. Q.A does not have any set up time but process steps like washing and machining have 50% and assembly even more. Hence, the machining cells are likely the systems bottleneck, based on the conclusion that the other cells are starved and waiting to work.

Consequently, 33-46% of the time the washing machine is not used and maintaining a high temperature is more efficient than constantly reheating the wash. However, a further review must be done. At an increasing volume will assembly and machining probably become bottlenecks causing disturbances and decreasing throughput. Yet, the assembly- and machining cells have a lower investment cost compared to e.g., leak test and washing, implying that more cells can be purchased if needed.

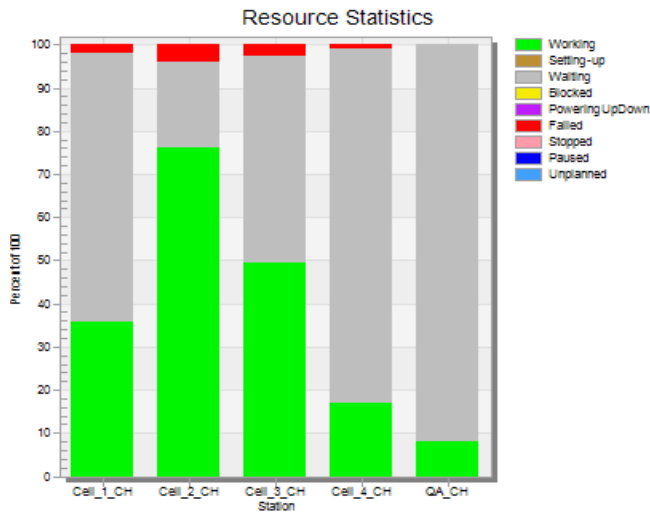


Figure 65: machining cells are working 74 % of the time at WIP 6 in the CH line.

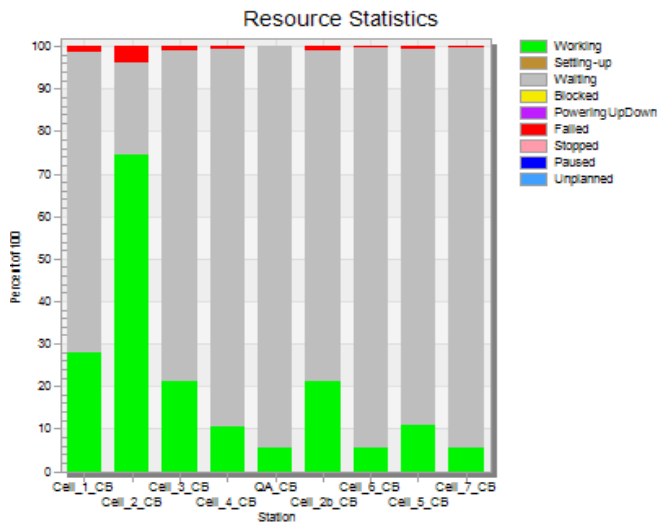


Figure 66: machining cells are working 74 % of the time at WIP 6 in the CB line.

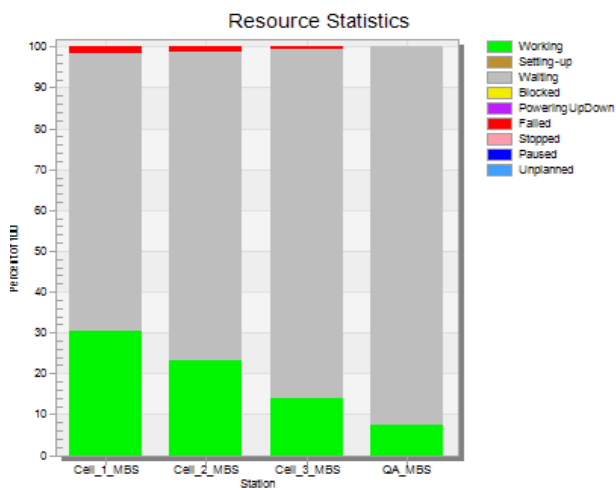


Figure 67: the equipment utilisation rate working % at WIP 6.

Analysing the breaking point for managing the JPH of 7, availability and WIP needs to be considered. A high availability assumes great maintenance, minimizing mean down time for example, or purchasing of more expensive machines. High WIP on the other hand in the simulation leads to more tied up capital in production and longer lead times.

Further on, higher set-up time is an undesirable consequence of manual loading. In concept one it is presented without set-up time because in the simulation 100 second was used and gave an excessively skewed image as a manual handling is closer to 10 seconds when standardized. Today it is by made by gantry loaders and it was difficult to find a suitable estimation. By adding set-up time JPH goes from been achieved at WIP = 3 and 6 from not achievable. Which is notably in a concept idea of dedicated flows.

Looking at availability for meeting the requirement of JPH = 7, is the demand reached at a level of WIP = 6 for CH and CB. It is reached at availability 98 % and 96 % respectively (see figure 68). However, the same throughput could be achieved at an increased WIP and a lower availability. The benefits of WIP = 6 are quick throughput with shorter lead time and less capital tied up in production. Speed often overcomes when comparing parameters in production flows.

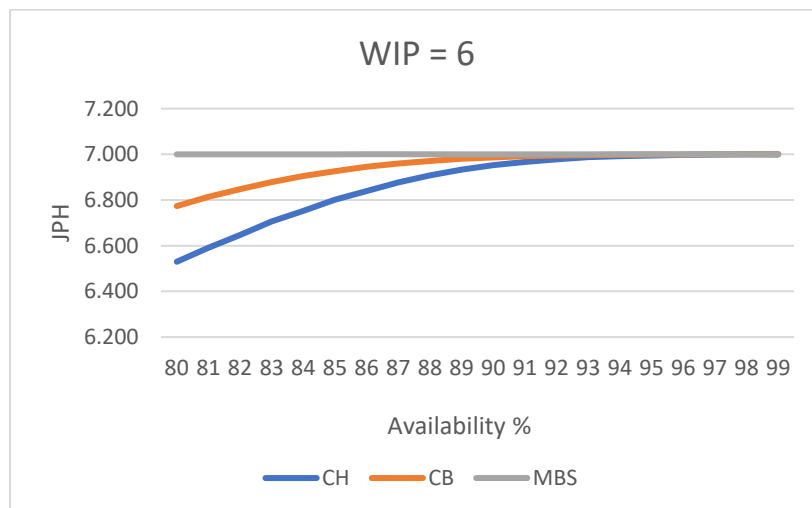


Figure 68: JPH and availability graph at WIP = 6

Lastly there is the MBS. Already at WIP 3 does this product reach the required JPH if the availability is 97 %. Can this availability stay be the lead time of 34 minutes. Looking at WIP 4 and an availability of 81 % has the led time increase to 43 minutes. Which is 25 % more time spent in line. See figure 69 below for WIP 3.

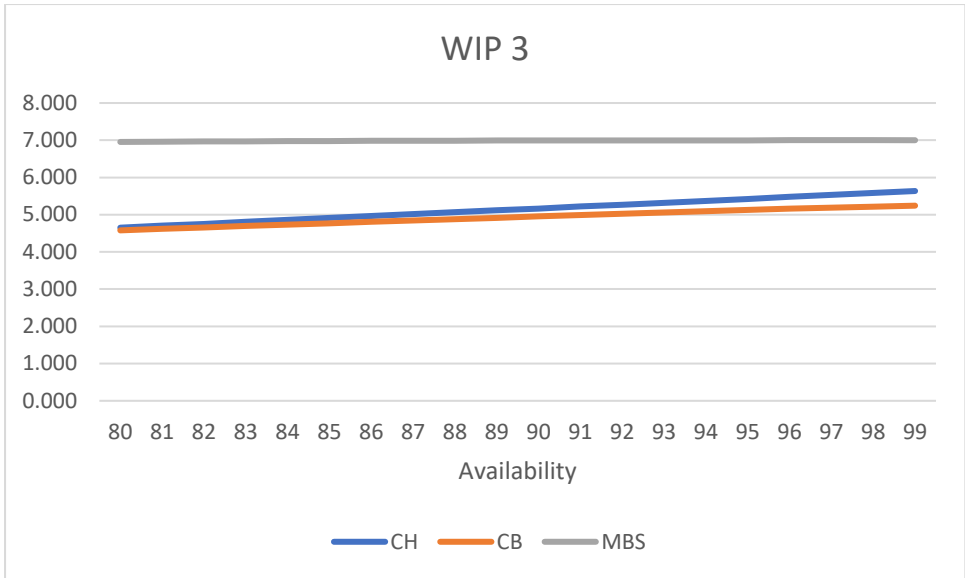


Figure 69: JPH and availability at WIP = 3.

The project team’s analysis of concept one with dedicated flows can be conducted like this:

1. The utilisation rate is low and there is a lot of no-adding value time.
2. MBS is optimised at WIP 3.
3. CB and CH are most efficient at WIP 6.
4. Machining is the process step taking the longest time.
5. By adding set-up time of 100 second the JPH will not be achieved.
6. By increasing the WIP can the required availability be lower.

6.2.4.2 Concept two- one line manufacturing three products

In concept two when comparing JPH towards an increasing WIP from 3 to 15 (see figure 70), there is a peak at 12 and stop at 15. JPH is 20 compared to 7 in concept 1 because here is one line instead of three (3 x 7 = 21). A higher WIP in concept one increases the JPH output but also a better lead-time but in concept two is not always the case (see figure 71 and 72).

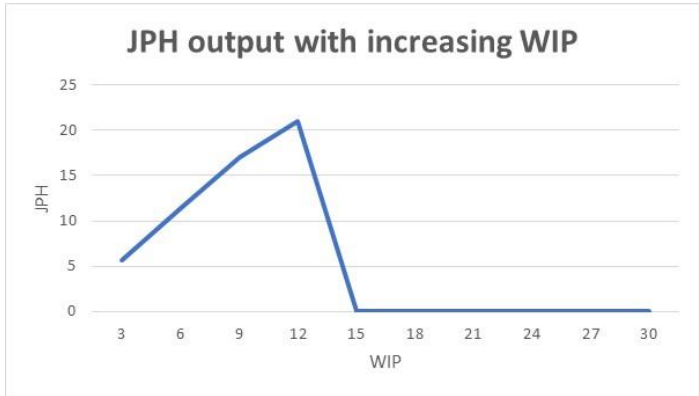


Figure 70: JPH output with increasing WIP for concept two.

Moreover, WIP = 6 the JPH increased to 11.4 as well as better lead time. It is a little bit more but still far away from JPH 21 and the utilisation grade is still a problem as it remains low.

At WIP = 9 the lead time is 37:05 minutes at 95 % and 35:37 at 99 % which is 40 seconds respectively 96 seconds faster than WIP = 6 at same availability level (see figure 71).

Comparing the JPH, an increase of 100 % can be observed when the WIP is increased from 6 to 12 in figure 70 but falls short of the target of 21 JPH. A direct result though of higher JPH is tied up capital increase, which generally has more disadvantages than advantages.

Also analysed was the WIP = 12, where results displayed prolong lead time, but JPH reaches almost reach the target of 21. The flow is not as smooth as earlier, but JPH increased almost 25 % compared to WIP = 9, which is good but at the expense of lead time. The WIP = 12 at 99 % availability has a lead time comparable to WIP = 9 at availability of 94 - 95 %. Looking at tied up capital it is also higher at this WIP. The project team identifies risks for WIP = 12 because it is sensitive for disturbance but could deliver the target JPH with some adjustment.

By analysing the occupation rate and the conclusion be made that an increase in WIP is equal to an increase in occupation rate. This event happens in each cell and at WIP = 3 and 6 it is less than 25% in each machine, therefore a lot of waiting time. At WIP = 9 and 12 is the occupation rate roughly between 25 - 40 % depending on cell.

The results above are before set-up time was added to the calculation and being added, the lead-time soared above three hours independent of WIP value but also a higher occupation rate (see figure 73). The first cell with RFID tag is most occupied with 75% occupation rate at WIP = 12. It can seem to be satisfying that the machine only is waiting 25 % of the time, but the difference 90% of the working time is set-up time.

By looking in more detail of the goal of 21 in JPH, one reason why the JPH does not reach 21 is that the mix of the universal fixture and ZPI. Constantly shifting fixtures etc. in order to manufacture products with different fixture system, implies long stand stills, waiting and blocking in the system. The universal fixture is built on the spot face concept, and by working with two different fixture system can several CB G1 be machined with other variants without remedying the construction constraint. However, it is at the expense of JPH.

The analysis of concept two with flexible flows can be concluded in following points:

- WIP = 12 is the has the potential of reaching the target JPH of 21.
- WIP = 9 has the best lead-time in general but only reach JPH 17.
- WIP can handle JPH 21 but is sensitive for disturbance at an availability level of 99%.
- Roughly 90% of the time in the cells is setting-up time.
- Applying different fixture systems leads to prolong set-up times.

WIP = 6			WIP = 9			WIP = 12		
Ava (%)	JPH	Lead Time	Ava (%)	JPH	Lead Time	Ava (%)	JPH	Lead Time
80	9,665	43:24.8381	80	14,166204	42:18.726:	80	18,1479	42:56.210:
81	9,7539	43:00.8540	81	14,285417	41:57.651:	81	18,3162	42:32.643:
82	9,8296	42:41.1575	82	14,416204	41:34.743:	82	18,4606	42:12.653:
83	9,9164	42:18.7219	83	14,540741	41:13.500:	83	18,5993	41:53.686:
84	9,9947	41:58.8130	84	14,665046	40:52.341:	84	18,7502	41:33.434:
85	10,074	41:38.9769	85	14,785185	40:32.231:	85	18,8949	41:14.346:
86	10,169	41:15.6241	86	14,9125	40:11.553:	86	19,0398	40:55.492:
87	10,243	40:57.6156	87	15,047222	39:49.878:	87	19,1894	40:36.342:
88	10,322	40:38.7708	88	15,181019	39:28.848:	88	19,3428	40:16.961:
89	10,407	40:18.8047	89	15,300926	39:10.268:	89	19,4891	39:58.796:
90	10,493	39:59.1440	90	15,440046	38:48.999:	90	19,6394	39:40.443:
91	10,579	39:39.5509	91	15,577778	38:28.415:	91	19,7794	39:23.625:
92	10,664	39:20.4695	92	15,713889	38:08.444:	92	19,9331	39:05.400:
93	10,749	39:02.0232	93	15,860185	37:47.207:	93	20,0762	38:48.631:
94	10,832	38:43.9929	94	16,010417	37:26.080:	94	20,2262	38:31.292:
95	10,921	38:24.8446	95	16,158333	37:05.401:	95	20,36	38:16.139:
96	11,007	38:06.9516	96	16,309028	36:44.749:	96	20,5037	38:00.012:
97	11,095	37:48.6702	97	16,472454	36:22.948:	97	20,6417	37:44.711:
98	11,184	37:30.7694	98	16,645602	36:00.145:	98	20,7681	37:30.917:
99	11,277	37:12.1136	99	16,827315	35:36.906:	99	20,8917	37:17.615:

Figure 71: Availability and lead time at WIP 6, 9 and 12 for concept 2 before set-up time.

WIP = 6			WIP = 9			WIP = 12		
Ava (%)	JPH	Lead Time	Ava (%)	JPH	Lead Time	Ava (%)	JPH	Lead Time
80	3.95366	3:30:12.8657	80	4.360030	3:30:15.2854	80	4.694067	3:43:47.1184
81	3.86294	3:30:58.3247	81	4.277858	3:31:13.5238	81	4.778450	3:44:29.7827
82	3.90121	3:30:26.1521	82	4.288548	3:30:32.0062	82	4.709387	3:43:52.5474
83	3.88385	3:30:20.3856	83	4.263352	3:31:32.0143	83	4.728129	3:42:52.9290
84	4.02090	3:30:07.0910	84	4.338604	3:32:11.1163	84	4.708929	3:43:44.5373
85	3.95159	3:28:22.2439	85	4.349449	3:29:51.7062	85	4.783693	3:42:32.6177
86	3.77390	3:30:45.2613	86	4.281981	3:29:41.6611	86	4.818934	3:41:43.3514
87	3.91384	3:28:48.7558	87	4.406531	3:28:59.4409	87	4.879550	3:42:02.8568
88	3.85842	3:27:59.3260	88	4.367807	3:27:46.7923	88	4.954031	3:40:34.0544
89	3.74387	3:29:38.3578	89	4.340956	3:29:49.1761	89	4.656924	3:42:40.1884
90	3.83151	3:29:09.2793	90	4.246584	3:29:52.6823	90	4.870273	3:40:38.2261
91	3.93016	3:28:27.3817	91	4.290909	3:28:22.6062	91	4.842795	3:41:46.1509
92	3.80232	3:28:01.7967	92	4.229852	3:28:09.1451	92	4.754621	3:41:14.8508
93	3.85352	3:28:16.0487	93	4.428860	3:25:39.9037	93	4.705070	3:40:29.7472
94	3.82467	3:28:03.3386	94	4.356187	3:28:35.0641	94	4.786831	3:39:43.8852
95	3.80589	3:26:22.0153	95	4.301606	3:27:50.3073	95	4.763286	3:40:23.6194
96	3.99701	3:25:29.2512	96	4.310352	3:26:46.0437	96	4.736013	3:40:07.4435
97	3.96883	3:25:42.6256	97	4.408325	3:27:32.2952	97	4.705409	3:41:10.0514
98	3.92837	3:24:28.2628	98	4.402728	3:28:00.1121	98	4.821651	3:38:39.3598
99	3.97043	3:23:47.7098	99	4.355058	3:25:56.0929	99	4.772099	3:39:23.2630

Figure 72: Availability and lead time at WIP 6, 9 and 12 for concept 2 after set-up time.

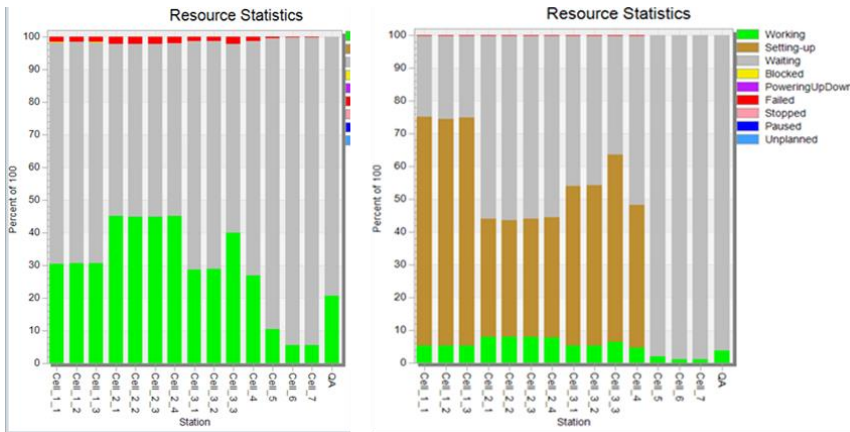


Figure 73: Resources statistics of each station how many percent utilisation for concept 2 at WIP = 12 before and after set-up time being added.

6.2.4.3 Concept three – One line with capability of manufacturing both VED and VEP CH, both generations, and CB, generation three

In the third concept was CB G1 excluded because of the construction constraints and to elaborate whether complete utilisation of ZPI could influence throughput and set up time. ZPI is as already discussed at several occasions not implemented for CB gen 1 but CH for gen 1 and gen 3 as well as CB gen 3 are compatible with ZPI. Therefore, a simulation of all these six variants could give insights for evaluate the flexibility today.

As figure 74 displays, the JPH maximum is 10.5 and is reached at WIP = 9. By increasing the WIP the lead time increases (see figure 75) but compared to earlier concepts WIP can go from 9 to almost 33 before the flow get jammed. The utilisation grade is still at low rate (see figure 76). A positive output from the simulation compared to concept two is that set up time is reduced from around 90% of the time it is working around to 15-25 % of the working time. A likely explanation is the unitary use of ZPI for all products manufactured in the system.

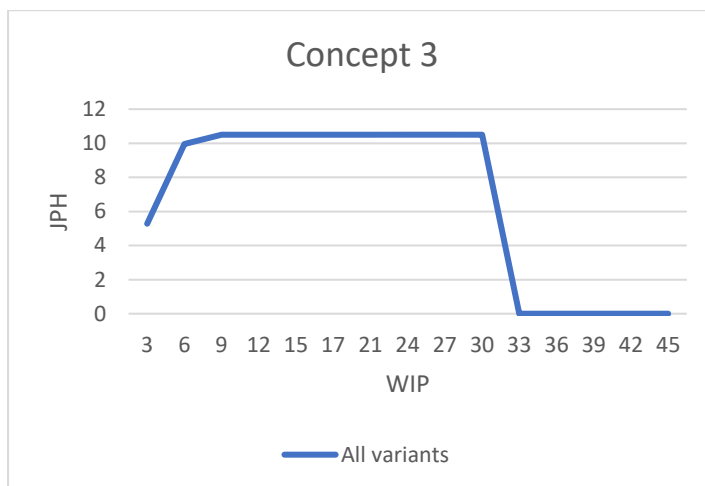


Figure 74: JPH and WIP for the concept 3.

By removing generation one and focus on the four variants in generation three, the JPH in this concept increase to 11 at WIP = 9, indicating complexity in the system composed of variation and unevenness.

There is a massive decrease in set-up time from 50 % in concept one and 90 % in concept two, to 15 – 35 % in concept three. An exception is Q.A with no set-up and machining and washing with 15%. The outcome indicates that ZPI is a tool that can provide standardisation in flexible production concepts and reduce the risk of unwanted complexity. Moreover is the ZPI an example of DFM since the manufacturing process has been taken into account when designing the product.

The simulation can be summarised as follows:

- Concept three struggles to reach JPH, probably because of complexity and unevenness.
- Good JPH and best lead-time at WIP = 9.

- Removing generation does not solve the JPH but decrease set-up time compared to the other concepts.
- The simulation highlights the benefits of a unitary fixture system, e.g., decrease in set up time from 50 % and 90 % in concept one and two respectively, to 15 – 35 % of working time in concept three.
- By remove variants through ZPI less complex latching appear.

WIP = 9			WIP = 12		
Ava (%)	JPH	Lead Time	Ava (%)	JPH	Lead Time
80	8,169367	1:13:26.8330	80	9,122685	1:25:30.4307
81	8,19213	1:13:14.5925	81	9,14429	1:25:18.4556
82	8,207948	1:13:06.0820	82	9,163002	1:25:08.3411
83	8,234375	1:12:51.5214	83	9,183063	1:24:56.9917
84	8,250386	1:12:43.3313	84	9,197145	1:24:48.4770
85	8,268711	1:12:33.5470	85	9,215278	1:24:39.0984
86	8,283758	1:12:25.4068	86	9,245756	1:24:21.6480
87	8,304784	1:12:14.6054	87	9,255015	1:24:17.2939
88	8,328511	1:12:02.5613	88	9,271798	1:24:07.6298
89	8,341049	1:11:55.6576	89	9,28588	1:24:00.7176
90	8,357446	1:11:47.2797	90	9,305748	1:23:49.9260
91	8,372685	1:11:39.6216	91	9,331211	1:23:35.7158
92	8,39159	1:11:29.3953	92	9,342785	1:23:29.6135
93	8,397184	1:11:26.4329	93	9,362461	1:23:18.6121
94	8,411651	1:11:19.4186	94	9,381752	1:23:08.4842
95	8,426312	1:11:11.8173	95	9,403164	1:22:56.7249
96	8,435764	1:11:06.9567	96	9,423804	1:22:46.0211
97	8,448881	1:11:00.1654	97	9,445988	1:22:34.8143
98	8,452546	1:10:58.1128	98	9,45679	1:22:28.7036
99	8,467785	1:10:51.4138	99	9,453511	1:22:30.5210

Figure 75: Availability and lead time at WIP 9 and 12 for concept 3.

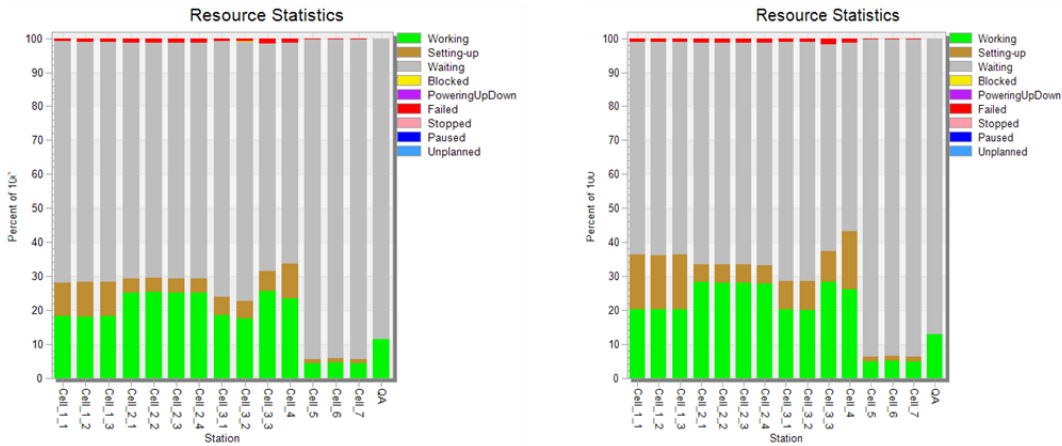


Figure 76: Resources statistics of each station how many percent utilisation for concept 3 at WIP 9 respectively 12.

7. Future research

The edge of knowledge has been pushed further but research never ends. For future research in this context and development from here and even further has the project team identify five areas.

1. Further sustainability work with Scope 1

The plant in Skövde already done a lot of work at scope 1, “the smoke from the chimney”. Renewable electricity, reusage of cutting fluids and water as well as energy losses related to the processes are reused in other applications. Scope 1 is a step, but still further work needed to reduce the emissions allied to material and the technology, e.g., the block made of aluminium or the combustion technology. Can it be more recycle aluminium without missing requirements concerning *critical to quality (CTQ)*? An interesting field that needs future research.

2. Standardisation

In both quantitative and qualitative data collection the project team identify the importance of standardisation in order to be flexible. The possibilities of bend and twist production starts at having a solid foundation based on standardisation. If the same methodology is applied, will the possibility to manufacture many variants and products with fluctuating volume be greater. In this thesis work the focus has been on new perspectives and concepts at an early stage. How to implement and how to standardise remains as important question to solve.

3. Tools

In a late stage of this project the number of tools possible for a machine to handle became a concern. There is a maximum of how many tools the machine can hold at once. To make both CB and CH in the same production line would demand more tools. Further research must be made on how many unique tools exist per product and how the manufacturing technique can be optimised in order to produce more products with less tools.

4. Construction constraint

The bill of process showed that generation one cylinder block does not use ZPI as fixture system and instead spot face. This was caused by a different construction and there are difficulties in making new construction and solving the issues have previously been determined to be time consuming. ZPI for generation one cylinder block is a standardisation that would save both investments in machine and time in production. ZPI is one step in making more flexible production that Aurobay should persist.

5. Flexibility at Aurobay’s factories.

Flexibility has been compared at the factory between assembling, machining, and support function. At this level the project team could find differences in the definition of flexible production. How consistent or different is the factory in China and Sweden? What advantages are there in talking the same way about flexible production needing for the demand of tomorrow?

8. Conclusions

The conclusion chapter aims to provide a concise and comprehensive summary of key findings of the thesis work. Through an in-depth exploration of the topic, the project team has examined various factors and meaningful insights.

With help of the selected methodology was the project scope defined and the requirements related to customer satisfaction and needs were identified in the *Voice of the Customer*. By learning how machining operations had been executed in the past and how the processes had developed during the years, in addition with the general progression and changes in the world, did the team understand *why* low volume production is needed at Aurobay. The rapid development regarding emission legislature and technology enhancements were two factors. Several project benefits (see table 11) were established in order to evaluate the associated profits and outcomes.

Table 11: the project benefits. The same table can be found under chapter 1.3.3.

Project benefits	
Hard	Soft
Machined cylinder heads- and blocks and bearing brackets	Flexibility understanding
Improved ability to meet customer inquiries	Mapping of products, variants and processes
Increased equipment utilisation	Low machining concepts with comparative analysis

Two research questions could be framed and were as follows:

- a. Define and develop an understanding of what flexibility is in relation to customer expectations.
- b. Deliver machining production concepts capable of manufacturing low volume according to characteristics identified in voice of the customer.

Furthermore, was a comprehensive theory study made to identify what the world already knows about the problem and consequently the knowledge limit was recognised.

Early on did the team learn that the term flexibility had broad and wide area of application, potentially leading to confusion and misunderstanding. Flexibility has been subject to studies in the past revealing several kinds of flexibility depending on what system capability is prioritised, e.g., system capability to manufacturing different volumes or products. Despite the previous findings was it necessary to enquire what kind of flexibility that was desired of the customer in question.

Hence, the project team initiated an inquiry consisting of framing and understanding the knowledge edge of today, how other automotive companies work with flexibility and how people with significant work experience at Aurobay defined and considered to be important for flexibility. By interviewing several departments about flexibility at Aurobay several departments but also at Volvo Trucks Tuve were qualitative data collected. Standardisation,

system thinking, takt, department culture and splitting operation to smaller chunks were key outcomes and elements for success in flexible production. By linking the key elements in a Kinship Chart could standardisation seen as the root and as fundamental for the supporting and create stable foundation on for develop system thinking among the whole company at each department. Even if resemblances on how departments defined and what they regarded as enabling factors for flexibility, did the team found it necessary to determine whether the findings could be proven or had to be rejected. Thus, by applying statistical tools could the significant differences be studied as well as potential other important factors.

However, statistical tools require either attribute or continuous data in order to display e.g., how variable X relates variable Y, and consequently the team was required to design a quantitative data test. The team recognised that the most suitable data type was discrete (attribute) since the difficulties of design a test consisting of variable data when defining flexibility was identified. Length, time, temperature, weight and so are variable data (continuous), which the project lacked and a test consisting of data with clear boundaries (good/bad, on/off, yes/no, categories etc.), i.e., attribute data, was identified to be more able.

The selected method was *the attribute agreement analysis*, which is a method used to determine if the appraiser's judgments are consistent or not and how the judgements vary between appraisers, i.e., repeatability and reproducibility, and is applied when the data is of the attribute characteristic e.g., no/go- and yes/no decision. Hence, the team designed a yes- and no question survey based on the outline from the qualitative data collection and three representative departments were identified as sample groups after discussion with the team's Chalmers supervisor, Peter Hammersberg. By just offering two options the judgments between the groups be studied.

The agreement analysis and hypothesis presented the following key outlines:

- When asked is it equally important for flexibility to have variable volume and ability to produce diverse variants and products. This can be observed at both the kappa values and the mosaic plot for question number seven.
- In most instances both abilities to change volume and manufacturing multiple products must be valid.
- Case one, two, five and six have the greatest uniformity between the sample groups. Number six is the direct opposite of number one.
- Rigid production flows like case number six are regarded to be the least flexible concept.

Additionally, the team found that assembly sample group had a strong department mindset and consensus regarding how they define flexibility, but both machining and support function sample groups see factors such as volume and variants of varying value.

The collected data, both quantitative and qualitative, were interpreted in a cause and effect diagram (see figure 77), there the interaction between different inputs can be analysed.

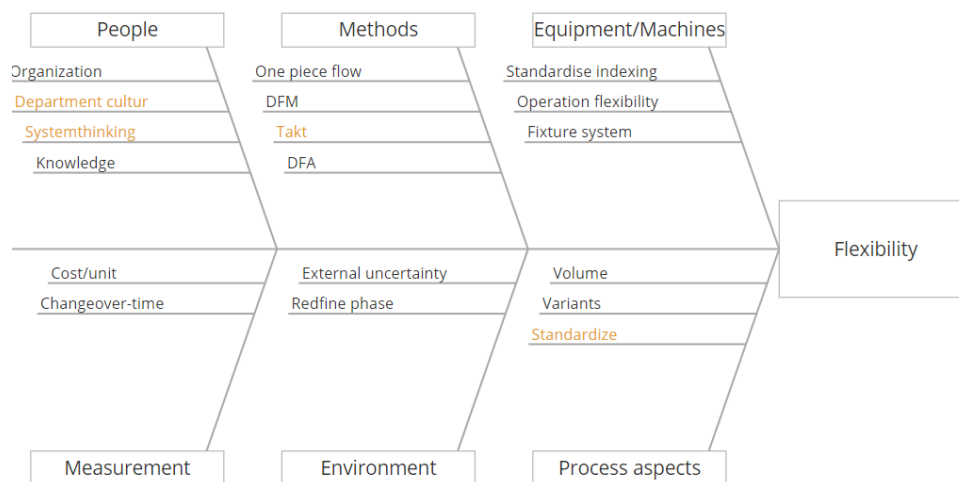


Figure 77: the cause-and-effect diagram for flexibility. The diagram is also found under 6.1.2.

Based on the findings from the data collection could a flexibility definition be agreed upon.

“A flexible concept is well standardised and the people and machines within and around the concept are organised for handling variation in volume and products. Machines are likewise capable of manufacturing multiple variants and products. The concept is ready for adaption as well as redefinition of new strategies for meeting the market demand. Flexible concepts are built with a system thinking and can handle change in culture, workforce and management”.

To help with work in the future related to flexible production concepts were three discussing points developed:

1. What is prioritised?
 - a. *Is it Volume?* Think of the quantity of machines and bottle necks.
 - b. *Is it Variants?* Think of Heijunka, multifunctional tools and move out variation that cannot be standardised in parallel and supportive flows.
 - c. *Workforce?* Flexible schedule and simplified learning.
 - d. *Product X?* Multifunctional tools, installation and competence among employees.
2. Can good flexibility here make flexibility worse somewhere in the value chain? Can this contribute to suboptimization instead of flexible system for us?
3. How can it be standardised for long-lasting flexibility?

Additionally, was implementation plan established ensuring that the definition will be applied correct and accordingly as well as ensuring long-lasting effect.

The second research question stipulated that the team should develop productions concepts with capability of machining parts in low volume according to the voice of the customer. Since three products were included in the project scope was the first step was to map and understand the processes and products. By reviewing the *bill of process* could process steps necessary to manufacture each product be identified as well as constraints related to processing.

One key finding was the major difference in fixture system between generation one- and three-cylinder blocks. CB G1 utilise a spot face system instead of the *zero-point index system*, creating a major difference on how clamping is done while machining. The research revealed that enquiries in the past had looked at the possibility of adding ZPI to the CB G1, but came to the conclusion that costly and time-consuming construction adjustments had to be made and thus was the suggestion dropped. However, has a recent project developed a universal fixture concept that uses ZPI as a base and then applies unique product addons to unlock the possibility of manufacturing several products in the same machine.

Besides from pure machining activities were also washing, leak tests and final inspection as recognised and mapped accordingly. The mapping did also show that cylinder block requires honing of cylinder strokes and main bearing guides, which exclusively can be executed in dedicated machines as of today. Of importance were also the products cycle times concerning machining, leak test, washing etc. which upon the number of needed cells could be calculated in relation to the customer demand. The cycle times were retrieved from value stream maps, completed by Aurobay. Depending on the asked yearly volume will the number of machines vary.

After collecting relevant data, were requirements and inputs needed for generating concept ideas interpreted in fish bone diagram (see figure 78).

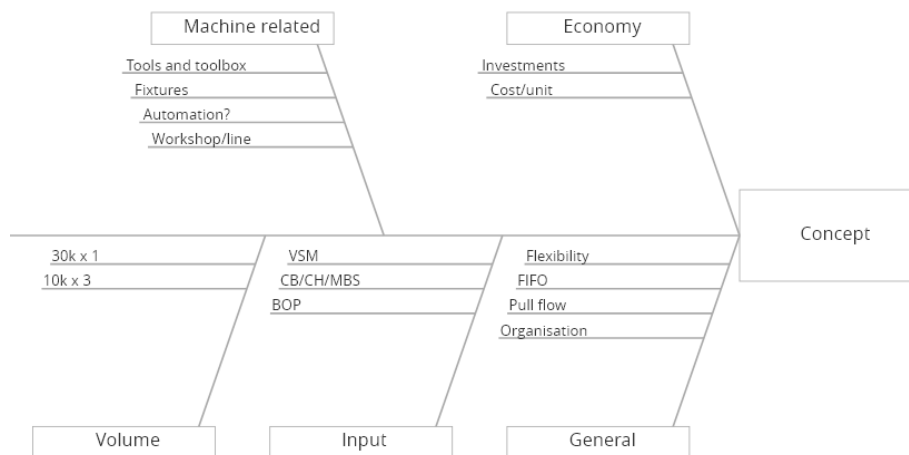


Figure 78: the cause-and-effect diagram presents the necessary inputs prior to generating concepts.

With regard to the identified inputs, the flexibility definition and other customer expectations identified in the VOC were in total three concepts elaborated. According to the VOC should two concepts be examined but however, the team did, as discussed earlier, recognised that the ZPI fixture system was the enabler for manufacturing multiple products and variants in one flow. Therefore, was a third concept only utilising the ZPI fixture system developed and simulated to give perspective to the customer and the other concepts.

All concepts are partially based on *Toyota Production System* (TPS) with pull and continuous flow, standardised work and smart automation. TPS is heavily associated with high end production flows where quality deviations and wastes virtually are non-existing and continuous improvements paves the way for increased efficiency and utility. However, the

layout is job-shop inspired since the job-shop layout tends to support flexibility and low volume does not imply large lines with machines lined up in sequence. Low cost per unit must be balanced against the possibility of increased flexibility. Hence, the concepts are based on both TPS and more traditional approaches in order to create a synergy.

The subsequent step was to simulate the concepts and the outcome from the simulation runs are summarised in following four bullet points:

Concept one:

- The utilisation rate is low and there is a lot of non-value adding time. MBS is optimised to work when work in progress (WIP) is equal to 3, but and CH and CB when WIP is equal to 6, and in order to reach the desired jobs per hour (JPH). By increasing the WIP, the required availability lower, but lead-time increased.

Concept two:

- The concept almost reaches the required JPH at 21. However, the margin was small and at WIP = 12 was JPH = 20,9 achieved but is likely sensitive to disturbance. Still, utilisation rate at cell level is often no more than 50 %. WIP = 9 has the best lead-time for concept two at 35 minutes and 37 seconds compared to WIP = 12 at 37 minutes and 18 seconds (before set-up time).

Concept three:

- This concept could perform JPH 10.5 at WIP = 18 and therefore only halfway to reach demanded JPH. At WIP = 18 it starts to get blocked by the production of CH but at a cell level no higher utilisation rate than 55 % with set-up time included. The simulation of this concept WIP = 9 has a lead time of 1 hour and 10 minutes and WIP = 12 has lead-time of 1 hour and 22 minutes. The higher the WIP the higher lead-time in this concept, which can depend on block time and set up time.

General:

Standardised fixture system, like ZPI, is an enabler for manufacture several products and variants in one flow. Inquiries and development regarding further products, like the bearing bracket (represented by the MBS), must work with design for manufacture in order to create the prerequisites needed for the product. Such prerequisite is applying the standardised fixture system among others. Hence, the R&D should work closely together with the manufacturing engineering department to enhance the product manufacturability. Moreover, enhancements related to set up time reduction and Heijunka must be done. One step is applying ZPI but more work concerning adequate lifting devices etc. helping operators is required as well as more detailed planning such that the optimal order sequence can be obtained, minimising waste, unevenness and overburden. Additionally, the low JPH rate in concept two and three implies more detailed planning to avoid the system from looking itself and minimise wait and unwanted transportation.

Worth noticing is the significant difference in cycle time between products, there the most noticeable is difference of 16 minutes between CB and MBS. The difference amplifies the requirement of planning and levelling in order to generate a smooth and efficient flow.

Concept one is more dedicated in the regard that only one product and variant is manufactured but however, the machines and cells have the capability of executing multiple tasks and process steps which is one flexibility requirement.

The overall conclusion is:

- Flexibility is achievable according to customer expectations.
- Low volume dedicated lines are non-feasible.

Flexibility is achievable according to customer expectations in concept two and three since machines and cells are capable of manufacturing multiple variants and products and by incorporating DFM more extensively in product development could products be adjusted to the process capability. Besides, the chosen layout and TPS thinking promotes continuous improvements as well as adaption for new products and no limitations concerning further adaption and incorporation with other production systems exist. The simulations indicates that flexibility is feasible but may be on the expense of throughput and hence, more work must be done to remedy the low throughput rate in order to satisfy demand. An important understanding to achieve flexibility is *standardisation* is fundamental. For instance, mixing fixture system, done in concept two, creates wastes like waiting and decreases the throughput rate. Likewise is unwanted variation created. The simulation showed that significant decrease in set-up time if the unitary ZPI system was utilised.

Additionally, the investment calculations disclose long payback times and increased risk if purchasing completely new sets of machines. Also disclosed is that the payback time is significantly shorter if reusing already existing machines and equipment. Besides, reuse of existing machines and equipment decreases the lead time from customer inquiry to start of production since there are no delivery waiting time and the equipment only needs adjustments. Aurobay would also be likely to increase the revenue in the acquired equipment.

Low volume dedicated lines are non-feasible because of the low equipment utilisation rate and large investments. Even if the flexible concepts consist of more machines and cells, is it no need to purchase completely unique sets of machines since equipment can be shared between products. Yet, dedicated lines be a possible solution to deal with variation that causes to much interference and product complexity, i.e., a product distinguishing itself towards already existing products to the extent that it causes major process adaption and adjustments, is the recommended action to manufacture the product in a dedicated line. The foremost example in the thesis work is the CB G1.

Consequently, the recommendation concerning what to consider when developing a flexible production concept are:

- Job-shop layout should be combined with continuous flow, pull thinking, jidoka and heijunka.
- Standardisation. The concept should have standardised fixture system, e.g., ZPI, instructions and working methods. Working methods could for instance be the procedure how to deal with quality deviations or how sampling is executed.
- Push out variation. Products that distinguish too much towards the defined standardisation and thus causing unmanageable variation shall be pushed out to

parallel flows, dedicated lines or stipulate certain characteristics in the requirement specification as a supplier.

- Increase the rate of reusing existing machines and equipment in order to decrease the payback time and lead time from customer inquiry to start of production.
- Implement automation with regard to that automation might impose greater system complexity and lower the degree of flexibility.
- Enhance work with *Design for manufacturing* and *Design for assembly*.
- Apply the flexibility definition and flexibility discussion questions during projects.
- Work with the further research points identified by the project team.

When evaluating the identified project benefits (see table 11) to the project outcome are all soft benefits and two of three hard fulfilled. The company has gained a flexibility understanding and has been handed a comparative concept analysis as well as a mapping of products and processes. Besides, another direct benefit, not recognised in the benefits assessment, is the increased knowledge related to low volume machining. Looking at the hard benefits is the increased equipment utilisation up for discussion since simulation disclosed relative low equipment utilisation rate. Nevertheless, the multiple reasons and improvement suggestions have been presented above which could entail increased utilisation.

Hence, following research questions have been answered:

- a. Define and develop an understanding of what flexibility is in relation to customer expectations.
- b. Deliver machining production concepts capable of manufacturing low volume according to characteristics identified in voice of the customer.

Extensive work has been performed in order to define and understand what flexibility is in the context of Aurobay. The work has included both qualitative and quantitative measures and analysis as well as field visits. Flexibility is possible but suggested improvements and recommendations needs to be taken in to account. In the proceeding work have production concepts capable of low volume machining been elaborated. However, the thesis work did also identify several areas where further research needs to be done, paving the way for additional projects and works.

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Appendix

In the appendix contains charts, figures, diagram etc. not displayed in the main report.

Gantt chart

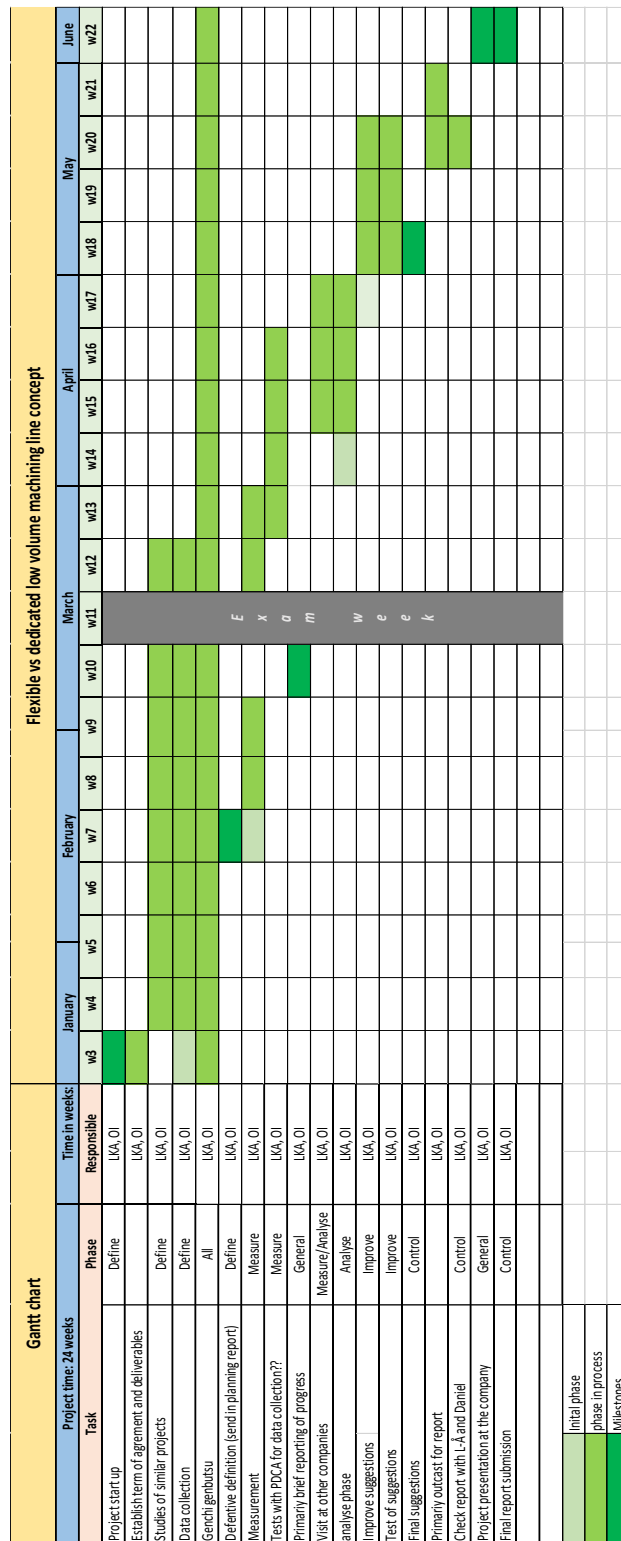


Figure 79: the project Gantt chart

Templates

Project											
Project team											
Description											
What does the data represent and how is the data collected?						Execution plan					
Unit	Is the data an input (Y), output (X) or process?	Measurement system	Lower spec. limit	Upper spec. limit	What and how?	Responsible	Frequency	Sample size	What do the subgroup represent ?	Data storage	Data reporting

Figure 80: the data collection template developed according to DMAIC standards used during the project.

Agreement and attribute analysis – flexibility survey

Abbreviations used in this survey:

- CB = cylinder block
- CH = cylinder head
- MBS = mass balancing system

Cases:

1. The machining flow can produce Gen 1 and Gen 3 CH, Gen 1 and Gen 3 CB as well as MBS. The takt can be changed between 5 and 14 takt an hour. Training of operators is not a requirement since the machine types are already in use at the company today.
Is the flow flexible? Yes or no?
2. The machining flow can produce Gen 1 and Gen 3 CH, Gen 1 and Gen 3 CB as well as MBS. However, the machines are delivered from a new manufacture, implying schooling and training of operators. The takt can be changed between 5 and 14 takt an hour.
Is the flow flexible? Yes or no?
3. The machining flow can produce Gen 1 and Gen 3 CH, Gen 1 and Gen 3 CB as well as MBS. Training of operators is not a requirement since the machine types are already in use at the company today. Yet, the takt is static (non-changeable).
Is the flow flexible? Yes or no?
4. The machining flow can produce CH Gen 1 and Gen 3 but no other product. The takt can be changed between 5 and 14 takt an hour. Training of operators is not a requirement since the machine types are already in use at the company today.
Is the flow flexible? Yes or no?

5. The machining flow can produce Gen 1 and Gen 3 CH, Gen 1 and Gen 3 CB, not MBS.
The takt can be changed between 5 and 14 takt an hour. Training of operators is not a requirement since the machine types are already in use at the company today.
Is the flow flexible? Yes or no?
6. The machining flow can produce Gen 1 and Gen 3 CH, but no other parts. Moreover, the takt is static (non-changeable) and the machines are delivered from a new manufacture, implying schooling and training of operators.
Is the flow flexible? Yes or no?
7. Broadly speaking, what is most important for flexibility according to you?
 - a. The takt is changeable
 - b. Multiple variants and products can be manufactured in the same production flow.
 - c. Both is equally important.

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