Development of a Highly Flexible Geometry Station for Versatile Production Systems in Automotive Body Construction

A Station designed for Joining of Body-in-White Assemblies during an Integration of Electric Vehicles

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Master of Science Thesis
Production Engineering and Management

Development of a Highly Flexible Geometry Station for Versatile Production Systems in Automotive Body Construction

A Station designed for Joining of Body-in-White Assemblies during an Integration of Electric Vehicles

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Abstract

The research in this report seeks to develop a highly flexible geometry station for joining future Body-in-White (BiW) assemblies. The goal is to eliminate the need for a complete reconstruction of a production line during integration of new car bodies in a contemporary production.

Today's BiW production is performed in sequential lines, where joining equipment is arranged in a specific order for each model geometry. An increasing model portfolio forces manufacturers to develop production systems that allow an integration of new models. Electrified alternatives of existing models are now developed and put into production. These models have similar appearance as conventional models, but with a completely different principle of driveline due to the propulsion. This means that new interfaces and platforms have to be developed and must now be integrated into a current production. Today's production lines are not prepared for coming changes, and current stations can only handle a limited number of variants. Integration of new geometries into a contemporary production line is not sufficiently efficient from a production perspective. The goal of the future is to make such an integration possible.

Initially, current and future production scenarios were studied. Based on this, four types of production scenarios, which a highly flexible geometry station can be integrated into, were set up. An integration can take place in different ways depending on how a highly flexible geometry station is compounded, therefore, different cases were created and compared in a case study. Internal and external benchmarking of production systems were made to compare the available solutions for increasing stations flexibility in a BiW production.

As reference for the project, a concept for a highly flexible geometry station has been developed and is therefore described initially before an additional depth has been realized. The further conceptualization of a highly flexible geometry in this report is presented in the form of a morphological composition of technologies that can increase a station's flexibility, as well as visualization of a station principles through layouts and cycle time charts. The result of the analysis generated several concepts that hold different degrees of capacity, footprint and flexibility. The focus was to achieve a high level of flexibility for integration of new models, with new geometries, in a current production. The conclusion was that the highly flexible geometry station can, in a contemporary production, produce independently in low volumes. Alternatively, produce higher volumes when it is integrated as a complement in a novel, not yet implemented, production concept.
**Keywords:** BiW; Body-in-White; Car body; Automobile Industry; Electric Vehicle (EV); New Product Integration; Flexibility; Changeability; Versatility; Modularity; Flexible Manufacturing System; Sub-assembly; Joining; Self-Piercing Riveting (SPR); Resistance Spot Welding (RSW)
Sammanfattning

Svensk titel: Framtagning av en högflexibel geometristation för mångsidiga produktionssystem inom fordonsindustrin

Forskningen i denna rapport syftar till att utveckla en högflexibel geometristation för fogningsav kommande Body-in-White-karosser (BiW). Målet är att eliminera behovet av en fullständig rekonstruktion av en produktionslinje under integrering av nya bilar i en samtida produktion.


Inledningsvis studerades nuvarande- och kommande produktionsscenarien. Utifrån det beskrevs fyra produktionstyper, vilket en högflexibel geometristation kan komma att integreras i. En integration kan ske på olika vis beroende på hur en högflexibel geometristation tillämpas, därfor jämfördes olika fall av det i en Case-studie. En intern och extern benchmarking av produktionssystem gjordes för att jämföra de lösningar som finns för att öka flexibiliteten i en BiW-produktion.

Som referensunderlag till projektet har ett koncept för en högflexibel geometristation tagits fram och är beskrivet inledningsvis innan en ytterligare fördjupning har realiserats.

Konceptualiseringen av en högflexibel geometristation i denna rapport är presenterad i form av en morfologisk sammansättning av teknologier som kan öka en stations flexibilitet, samt visualisering av en principiell station genom layouter och cykeltidsdiagram. Resultatet av analysen genererade flera koncept som innehar olika grad av kapacitet, fabriksyta och flexibilitet. Fokus var att uppnå en hög flexibilitetsnivå för integration av nya modeller, med nya geometrier, i en nuvarande produktion. Slutsatsen var att den högflexibla geometristationen kan, i en nutida produktion, producera självständigt i låga volymer. Alternativt producera högre volymer då den integreras som ett komplement till ett ännu inte implementerat nytt produktionskoncept.
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Zusammenfassung

Deutscher Titel: Entwicklung einer hochflexiblen Geometriestation für wandlungsfähige Produktionssysteme im Karosseriebau

Die Forschung in diesem Bericht zielt darauf ab, eine hochflexible Geometrie-Station für das Fügen zukünftiger Rohbau-Baugruppen zu entwickeln. Das Ziel ist es, die Notwendigkeit einer vollständigen Rekonstruktion einer Produktionslinie während der Integration neuer Karosserien in einer modernen Produktion zu beseitigen.


Als Referenz für das Projekt wurde ein Konzept für eine hochflexible Geometriestation entwickelt und im Rahmen der Thesis dokumentiert, bevor eine zusätzliche Tiefe realisiert wurde. Die weitere Konzeptionierung einer hochflexiblen Geometrie-Station wird in Form einer morphologischen Zusammensetzung von Technologien präsentiert. Dieser kann die Flexibilität einer Station erhöhen und zudem die Visualisierung von Stationsprinzipien, beispielsweise durch Layouts oder Zykluszeitdiagramme, fördern. Das Ergebnis der Analyse erzeugte mehrere
Konzepte, die unterschiedliche Grade an Kapazität, Grundfläche und Flexibilität beinhalteten. Der Fokus lag auf einer hohen Flexibilität bei der Integration neuer Modelle mit neuen Geometrien in einer aktuellen Produktion. Die Schlussfolgerung war, dass die hochflexible Geometriestation in einer zeitgemäßen Produktion in kleinen Stückzahlen produzieren kann. Alternativ ist die Geo-Station auch als Bestandteil eines noch umzusetzenden Produktionskonzepts integrierbar.
Declaration

This report has been submitted by Erik Knutsson to KTH Royal Institute of Technology, Stockholm. This report is completed for obtaining a Master's degree in the program Production Engineering and Management. The work has been carried out in cooperation with Daimler AG, Sindelfingen.

I hereby declare that the present work in this report is developed and written independently by myself and no other sources or means than those mentioned were used. I have attributed to the sources of information to the best extent of my knowledge about them.

________________________________________

Erik Knutsson
Sindelfingen, June 2018
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Erik Knutsson
Sindelfingen, June 2018
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### List of Abbreviations and Definitions

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<tr>
<td>AGV</td>
<td>Automated Guided Vehicle</td>
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<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
</tr>
<tr>
<td>BiW</td>
<td>Body in White</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber-Reinforced Plastic</td>
</tr>
<tr>
<td>Clinching</td>
<td>Metal-joining method for joining thin sheets without additional components.</td>
</tr>
<tr>
<td>CT</td>
<td>Cycle Time</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>FDS</td>
<td>Flow-Drill Screwing</td>
</tr>
<tr>
<td>FMS</td>
<td>Flexible Manufacturing System</td>
</tr>
<tr>
<td>Footprint</td>
<td>The outlines of a stationary plant on the ground in mechanical engineering.</td>
</tr>
<tr>
<td>GEO</td>
<td>Geometry</td>
</tr>
<tr>
<td>ICEV</td>
<td>Internal Combustion Engine Vehicle</td>
</tr>
<tr>
<td>Jph</td>
<td>Jobs per Hour</td>
</tr>
<tr>
<td>LCA</td>
<td>Low Cost Automation</td>
</tr>
<tr>
<td>MBC</td>
<td>Mercedes-Benz Cars</td>
</tr>
<tr>
<td>MFG</td>
<td>Multi-Flexible Geometry Station</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio-Frequency Identification</td>
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<tr>
<td>RMS</td>
<td>Reconfigurable Manufacturing System</td>
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<tr>
<td>RS</td>
<td>Respot</td>
</tr>
<tr>
<td>RSW</td>
<td>Resistance Spot Welding</td>
</tr>
<tr>
<td>SBS</td>
<td>SmartBodySynergy</td>
</tr>
<tr>
<td>SLT</td>
<td>Custom-build Storage Rack (Sonderladungsträger)</td>
</tr>
<tr>
<td>SM</td>
<td>Supermarket</td>
</tr>
<tr>
<td>SPR</td>
<td>Self-Piercing Riveting</td>
</tr>
<tr>
<td>TMU</td>
<td>True Mileage Unknown</td>
</tr>
<tr>
<td>ULT</td>
<td>Universal Storage Box (Universalladungsträger)</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
<tr>
<td>ZB</td>
<td>Assembly (Zusammenbau)</td>
</tr>
</tbody>
</table>
1 Introduction

This chapter describes the background to the problem this report addresses. A definite problem description is generated together with project objectives, research questions and the limitations of research in the project. In addition, a scientific methodology has been outlined for how the problem has been dealt with to gain a fundamental link to science.

1.1 Background and Company Description

Daimler AG has origins back to the invention of the automobile in 1886 and is today the parent company of brands such as Mercedes-Benz Cars, Mercedes-Maybach, Mercedes-AMG and Smart. As the world’s current leader in manufacturing of premium cars, Daimler is now exploring new areas due to the trend towards electrification of vehicles. Daimler is not only facing a completely new vehicle architecture, but also approaching new challenges within the production of cars.

The future car body will no longer be able to take place in a rigidly concatenated line due to the increasing variance of conventional models together with the increased number of electrified vehicles. A paradigm shift is unavoidable, since the increased car-body variants result in a use of new materials and consequently also strongly different joining methods.

At present, car-body construction at Mercedes-Benz Cars essentially consists of hundreds of welding and joining robots, which carry out their work one after the other in a defined order until the car body is finished and goes into the paint shop. If now the successor or a derivative of a model with different geometries need to be manufactured, then usually a second line must be built, which meets the specific requirements of the vehicle. For example, when diversified components for an electric vehicle are installed in a successor, grippers and fixtures need to be replaced to match the new geometries. Also, the joining methods and the sequence and settings of those require an update due to other material combinations. There are major differences in the architecture of electric vehicles. Instead of a combustion engine and transmission, an electric vehicle needs a large and relatively heavy battery, which must be integrated crash-safe into the vehicle floor. Such major changes in the architecture would require a complete new line in today’s production strategy.
In the automotive body assembly, a number of steps are performed to form a so-called Body-in-White (BiW). That is the used expression for a car-body that has been assembled completely, but not yet gone through painting. The first step of joining single parts into one compound assembly is made in a step called geometry station (GEO). The assembly is then transported to the succeeding step that is named respot station (RS). Here additional joints are performed for giving the assembly final strength.

Current geometry- and respot stations in today’s line are designed to join high volumes of pieces and therefore have a limited flexibility. Within the project SmartBodySynergy, a flexible production station is designed and virtually put into operation to ensure the future viability of the concept.

Today only a conditional number of variants can be joined in one geometry station. Therefore, the advantage of having a highly flexible geometry station is essential for the future integration of electrified vehicles. The target in this project is to develop and compare concepts for joining of newly integrated BiW-assemblies in a Multi-Flexible Geometry station (MFG). An MFG station should prove itself to be justifiable in terms of flexibility, footprint, and efficiency but also feasible for integration into a current production scenario.

1.2 Objectives

The objective for this research is to eliminate the need for a complete reconstruction of a production line during integration of new car models in various production scenarios. To reach the thesis objective, following research is performed:

- Identification of strategies in a scenario related to today’s BiW production.
- Market understanding of trends triggering a required change in current BiW production.
- Studies of the drawbacks in a current geometry station with respect to flexibility.
- Outlines in form of one or more feasible concepts of a multi-flexible geometry station integrated in a BiW production scenario, highlighting the most suitable solution in production of MBC. Aiming at a multi-flexible geometry station that can handle and produce different styles of assemblies within the same family. Thus, enabling a shorter launch period during integration of new car models.
To solve the problem of a new-model integration, a multi-flexible geometry station requires:

- To be integrated in a selected production scenario, current or future one.
- Capacity of handling 5 – 30 jobs/hour.
- Handling of different materials and geometries.
- Joining of different materials and geometries.
- Maximum floor utilization by aiming at a station with minimized footprint.

### 1.3 Research Questions

Following research questions were defined:

RQ1  Can a new model within the C- and E-class architecture of platforms be integrated and produced in an MFG station?  

RQ2  Can an MFG station be placed in an existing or upcoming production scenario?  

RQ3  Can it be feasible to perform reslot operations in an MFG station?  

RQ4  Can an MFG station have the capacity to replace a number of less flexible geometry stations?

### 1.4 Scientific Methodology

For gathering secondary data, a literature study is done in the area of flexible- and reconfigurable manufacturing systems and production technologies such as joining. Relevant data from previous work is collected from scientific search engines, among them KTH library, CiteSeer and Google scholar. Also, from internal standards, articles and applicable literature.

Furthermore, to meet the research objectives on a qualitative level, industrial and technical primary data is collected internally and externally. That is done by interviewing engineers, conducting observations and continuously confirming findings with responsible superiors. Additionally, a performed market analysis with focus on technologies, innovations, future trends, productivity and best practice.

### 1.5 Scope and Delimitations

The work in this report is towards a realization of proposed concepts for a future implementation. Main focus is to create MFG station concepts for flexible and modular production scenarios, and not for a conventional BiW line. The suggested concept of a multi-
flexible geometry station is restricted to joining of under-body assembly parts (rear floor, main floor and engine compartment). Joining of a subassembly requires several GEO-steps. This research focuses on the principles of a station containing more than one GEO-step. Therefore, the work is limited to four GEO-steps. Furthermore, the content of the work is primarily executed in the project SBS with focus on WP 1 and WP 2. Remaining WP: s in SBS will stand for a minor part.

In order to delineate the research within appropriate limits, following is precluded:

- Flow- and layout simulations of the concept.
- Profound study of the joining methods in this project. The relevant joining methods discussed are mainly resistance spot welding and self-piercing riveting.
- Detailed economic evaluation of respective concept.
- Operational aspects of the manufacturing process, such as production planning.
- Research in different software and PLC solutions.
- Practical tests within the conceptualization and analysis.
2 Car Body Manufacturing

This chapter describes levels of changeability in production systems and how it is related to car body manufacturing. It also defines the different layouts that a production can take place in. Furthermore, an explanation of the sequenced steps required in a serial production of car bodies together with a deeper study of BiW’ production.

2.1 Changeability in Car-Body Manufacturing

Changeability in a car-body manufacturing is an overall expression that holds terms such as changeover ability, configurability, flexibility, versatility and agility. For example, flexibility in terms of manufacturing is used in a wide-spread range. The definition “flexibility” is very general and must therefore be differentiated into sub-levels (Wiendahl, et al., 2007). There are numerous descriptions in literature for flexibility and versatility, which partially overlap in their description. To distinguish between these numerous definitions, the terms have to be put in context. In Figure 1, several terms are categorized with respect to the product and the production.

Figure 1 – Classes of factory changeability, adapted from: (Wiendahl, et al., 2007).

Figure 1 gives an overview of following descriptions (Wiendahl, et al., 2007):

- **Changeover ability** is the level of changeability when a station is shifting between different operations performed on a known workpiece.
- **Reconfigurability** is the changeability in a systematic arrangement of stations that can perform operations on a number of workpieces within a family. Reconfigurability is achieved through device changes or similar adjustments in a station.

- **Flexibility** is the term used when a part of the manufacturing system can change the production between workpieces with similar geometries within the same family. The manufacturing system includes a number of stations together with the logistical system for material supply to the arrangement of stations.

- **Versatility** is achieved when a complete manufacturing system can change the production between product families.

- **Agility** is the changeability in the complete network of a manufacturing company. Agility includes the development and production of products in necessary volumes at strategical locations for enabling new markets.

The research in this report will only consider reconfigurability, flexibility and versatility in further analyses.

### 2.1.1 Distinction between Flexibility and Versatility

Flexibility describes the ability of a production system to change with very little financial effort to adapt to a changed circumstance. The achievable system tasks are limited by capability corridors set at the time of planning (Abele, et al., 2006). For example, within these corridors a predetermined extent of quantity changes can take place.

The versatility, on the other hand, is described as the ability to transform a systems property for organizational, technical and logistical changes (Nyhuis, et al., 2008). The changes are performed outside reproached flexibility corridors of a production system in a short time, with low investment and taking the interactions of the system features into account (Zäh, et al., 2005).

This means that a versatile system can alternate between the flexibility corridors (see Figure 2). Versatile systems have therefore no explicit limits in their implementation and are largely solution-neutral (Cisek, et al., 2002).
2.1.2 Flexibility Types

Flexibility can be divided into several subgroups focusing on different areas in a system. In this research, it is chosen to focus on the three most critical types of flexibilities (Changa, et al., 2006):

- **New product flexibility** – The capability to design a current production system for the production of new models or a modification of current models.
- **Product mix flexibility** – The capability to alternate a production between models in a current portfolio.
- **Capacity flexibility** – The capability to adjust the volumes of a number of products in a production system for meeting demand fluctuations.

For market competition, the two most driving flexibility types in a system are the *product mix flexibility* and the *capacity flexibility* (Zhang, et al., 2003). However, today’s short model cycles of cars forcing car manufacturers to consider the new product flexibility in their production systems since it is the driving factor for the flexibility in the two other flexibility types. A production system that can choose the capacity in the process and alternate between models in a current portfolio, but also integrate new models in a current system, has a high level of total flexibility (Changa, et al., 2006). Figure 3 describes how the three flexibility types affect each other.
2.1.3 Changeability Enablers

In a changeable system, there are so-called transformations enablers for reaching high changeability. The transformation enablers are presented in Figure 4 enable a system to change the physical functionality within pre-defined boundaries on a factory level (Wiendahl, et al., 2014). The transformation enablers are not to be confused with the flexibility types.

The *universality* describes the properties of plant modules or elements for tasks, technologies, organizations or requirements and functions of a product to be usable. The property is achieved through appropriate dimensioning and design of the system modules achieved. *Mobility* enables free transport within a factory e.g. by a driverless transport system within a Body shop. *Scalability* describes the technical, spatial, organizational and personnel adaptation through expandability and reducibility. *Modularity* describes the interchangeability of functional, standardized units or elements through appropriate interfaces. Modularity include Plug & Produce modules such as tools that can be docked to a robot as needed. *Compatibility* is the networking ability understood material, information, media and energy (Wiendahl, et al., 2014).
A factory’s ability to adapt to changes and to reach a higher level of changeability is through the transformation enablers. The transformation enablers can be used by a factory planner in an early stage for implementing changeability in a factory (Wiendahl, et al., 2014).

2.2 Production Layout Strategies

A production layout for car-body production can mainly take four shapes depending on what type of vehicle is produced and what strategy the producer has. What separates them are factors such as capacity and variance flexibility.

The different layouts are explained as:

1. **Fixed-position layout** is normally used when producing large products or components. The production is adjusted to the product of each case (Omar, 2011). For example, manufacturing of extreme sports cars. The advantage is a high production flexibility since the production is arranged for each product case. The disadvantages are: a high number of transports, large footprint, and low capacity (Lindqvist & Johansson, 2016).
2. **Process-oriented layout** is an arrangement of machines and operations. It is typically used in workshops, which normally have a high number of variants in lower volumes (Omar, 2011). The production is not sequenced for a certain product and thus enables a high
flexibility. However, the layout normally comes with a complex material flow together with high buffers (Lindqvist & Johansson, 2016).

3. **Product-oriented layout** is planned to match the sequenced steps in the manufacturing of the product. This allows higher volumes, but with the consequence of a lower product variety due to low flexibility (Lindqvist & Johansson, 2016).

4. **Cell layout strategy** can be described as a mix of the process-oriented and product-oriented layout. This enables a medium volume output together with higher product variety than the process-oriented layout (Omar, 2011).

Omar (2011) defined that the optimum choice of layout depends on factors such as: production time, production cost, type of material handling, investments, factory footprint and flexibility.

Generally, for serial production of cars, the **product-oriented layout** is applied as a line. In this research, the outcome of an MFG station is as a **cell layout strategy**. All required operations to form an assembly are together in one station, but the sequence between them can be interchangeable. A variable sequencing enables the station to produce different types of models by the change of tools.

### 2.3 Changeable Manufacturing Systems

In previous chapters, flexibility and reconfigurability have been defined. These two definitions transferred to actual production systems lead to so-called Flexible Manufacturing Systems (FMS) and Reconfigurable Manufacturing Systems (RMS). The definition of each system are presented, cited from (ElMaraghy & Wiendahl, 2009).

> “Flexible manufacturing allows changing individual operations, processes, parts routing and production schedules. This corresponds to variations in products within a pre-defined scope of a parts family. It also allows adjusting production capacity within the limits of the existing system.”

> “Reconfigurable manufacturing allows changeable functionality and scalable capacity by physically changing the components of the system through adding, removing or modifying machine modules, machines, cells, material handling units and/or complete lines.”
In Figure 5, three types of production systems are described with respect to product variety and the system capacity. Dedicated Manufacturing Lines (DML) are developed for high volumes of in a low product range. FMS are developed for a high flexibility between products in a current portfolio, to the consequence of a lower capacity. RMS systems can be scalable for changing volumes and configured for product changes. The background to the development of RMS is based on the limitations identified in a FMS. An FMS is very flexible within the range of products it was built for, but not flexible for changes. The RMS does not rely on the in-build flexibility as an FMS; instead, RMS focuses on the principle to rebuild parts of the system but utilize current machines. Each rebuilding process in a RMS is driven by product changes (Diffner, 2011).

During the nineties, car-body manufacturer invested in FMS with a vision of reusability for upcoming models. However, new materials together with new geometries and short model life-cycles made the FMS financially unprofitable (Meichsner, 2009).

![Diagram of DML, RMS, and FMS](Al-Zaher, 2013)

2.4 Manufacturing Cycle Time and Takt Time

The separation of takt time and cycle time is important for further calculations of the capacity in each production station. Takt time is described as the time for each product to be produced in order to meet customers demand. Cycle time is the actual time each process step takes to be finished (Balaji, et al., 2016). Manufacturing cycle time length require to be less or same as the takt time if the production goal ought to be reached. It is important to match the manufacturing
cycle time with the takt time to avoid overproduction and unnecessary buffers. In case the losses have been counted away in the takt time, the manufacturing cycle time will be represented only by process cycle time. Generally, process cycle time can be separated into productive time and non-productive time, which is described in Figure 6. Within the productive time, value-added activities are performed, such as welding, self-piercing riveting, adhesive bonding, etc. In the non-productive time, activities that do not bring value to the product, but are necessary to perform for further production, are executed (Balaji, et al., 2016). For instance, moving the part to joining position, indexing between joining spots, transportation in the station and changing of tools.

Reducing the productive time often require investments of new- and faster machines or equipment. Therefore, when a cycle-time analysis is carried out, the focus lies within the reduction of non-productive time. A non-productive time is generally not avoidable but can often be reduced by an optimization of current material flow and part handling (Balaji, et al., 2016). Nonetheless, an increased cycle time due to stoppage can be reduced to zero in the best scenario. The stops are mainly depending on preventive maintenance and incoming quality-control system.

![Figure 6 – Subordinated parts considered during a manufacturing cycle time analysis.](image)
2.5 Activities in Automotive Assembly

Automotive production is separated into powertrain- and assembly divisions. In a powertrain production, engine and transmission parts are manufactured for the complete drivetrain. However, in an assembly process, joining of the complete car body and assembly of the final car is performed. This research is primarily focused on the assembly division and this chapter will therefore only describe the process steps in such a production.

The main activities in a conventional assembly plant are sequenced in a certain order, shown in Figure 7. It can superficially be described in five steps: stamping, joining, painting and final assembly. The final testing is not considered as a part of the assembly plant, but is performed after the final assembly step. In addition to manufacturing of car bodies, the assembly plant also holds the marriage of driveline to car body and processes the final steps for the car before delivery (Omar, 2011).

![Figure 7 – Activity flow in automotive manufacturing (Kiefer, 2007).](image)

2.5.1 Stamping

In the stamping plant, geometrical shapes are produced from coils of thin aluminum- or steel sheets. Complex shapes are formed via high-pressure presses, either hydraulic or mechanical, and further sent to joining (Omar, 2011).

2.5.2 Joining

In this step, the so-called BiW structure is assembled. The materials and joining methods applied in this step are further described in detail under Chapter 2.6.

To begin with, the first joining steps form subassemblies, for example: inner- and outer body sides, rear floor, main floor and engine compartment. These steps also include joining of doors, trunk lid, and engine hood. In this report, these parts are further described as hang-on parts, because they are not permanently joined to the complete car body.
Succeeding step is the final joining of subassemblies, in this case joining of rear floor, main floor and engine compartment will together complete the underbody of the car (Omar, 2011). After several subassemblies have been joined individually, they are mounted together in a final line. This step is named “framing” and involves the joining of the inner- and outer body with the under- and upper body. Finally, hang-on parts, like: doors, front fenders, hood and trunk lid are mounted and adjusted (Omar, 2011). After this step, a complete BiW has been assembled and is ready for painting.

2.5.3 Painting

In the paint shop, the car body acquires all the required sealing for corrosion resistance. First, the car body is transported through a bath for hot-dip galvanizing or electro galvanizing where a layer of zinc is applied to protect the steel against corrosion. This is followed by several booths with integrated robot systems that apply layers of primer, top coat and clear coat on the car body. In between the applying of each layer, and for the final step, the cars go through ovens for drying and hardening of the paint and other sealing (Omar, 2011).

While nozzles and equipment must be cleaned after each color change, the paint shop attempts to paint in batches to reduce changeover time and waste. Therefore, it is not unusual to have an altered main sequence of cars in the paint shop. However, it is important to restore the sequence before the cars leave the paint shop for the upcoming step (Omar, 2011).

2.5.4 Final Assembly and Testing

The car body is delivered directly from the paint shop to the assembly area. The main event in the final-assembly area is to merge drivetrain together with the car body, internally named “the marriage”. Interior, chassis components, wheels, exterior parts and other trim are also mounted in the final step. The stages are mainly containing manual assembly processes with ergonomic tools for required operations (Omar, 2011). Although, a number of automated processes may be found for assembly of larger parts such as, windshields or dashboard.

After the car has been assembled completely, it will endure a number of tests to verify the function and quality before final delivery (Omar, 2011).
2.6 Body-In-White Production

The Body-in-White refers to an assembly of single metal sheets that have been joined together to form the shell of a car body. The term BiW is used for the car body until it has been painted (Ishaya, et al., 2014). A BiW is both the most expensive part in the whole car manufacturing and the part that is subjected to the most changes due to the market trends (Shalash, 1996).

2.6.1 Assembly Process in a BiW production

Car-body manufacturers have different strategies in how to assemble vital parts to a BiW structure. Figure 8 describes a flowchart of how Daimler AG assembles their BiW. Daimlers approach is to have the assembly in three sequential mainlines with separate side lines paired to each main line (Kiefer, 2007).

In the first step, subassemblies (ZB) of underbody parts are delivered in matching sequence from three separate sidelines. In Z1, the three parts are joined together to compose a complete underbody platform that forms the foundation for further work.

The next step is the framing, which is done in the Z2 line. In Daimler’s production, the Z2 main line is separated into three subordinated steps. The inner- and outer side walls are attached in sequence to the underbody from both sides. Additionally, the roof is attached in the last step of the framing line.

In the end, the car travels through the main line Z3 for the mounting of all hang-on parts. The hang-on parts are not permanently joined to the car body since they are supposed to be replaceable if damages occurs (Kiefer, 2007). The complete car body is assembled completely before painting to avoid changes in color shades between the body and the hang-on parts. After the paining, a number of hang-on parts are dismounted from the car body to be assembled separate with interior parts. The hang-on parts then return for being mounted to the matching car body number during final assembly.
2.6.2 Geometry- and Respot Processes

In following paragraphs, the difference between a geometry operation (GEO) and a respot operation (RS) is defined. A station that holds a geometry operation has facilities that serve to ensure the geometry between two or more components. In this case, certain sub-components of the assembly are brought in the GEO station. The parts are placed in a fixture where stationary clamping components hold the part in the desired position. Next, joining points is performed to create a geometrical subassembly from the single components. However, the assembly has only been given the joints required to keep its geometry and not all the joints for final strength.

After the GEO operation, the assembly is moved to the RS operation. Here, with the help of additional joining steps, the connection of the components with each other is strengthened. During an RS operation, the assembly does normally not require a rigid fixture for holding the parts together during joining.
2.6.3 Material Mixes in a Car Body

Car manufacturers strive for lighter car bodies to reduce the amount of CO$_2$ their products emit (Kaščák & Spišák, 2013). There are several approaches for achieving a lightweight construction. The utilization of carbon fiber-reinforced plastic (CFRP) structures in a car body is a hot topic. The current prices for complete CFRP structures are still relatively high and not suitable for mass production. Therefore, complete CFRP assemblies can only be found in luxury models or sport vehicles. However, CFRP materials are also implemented in mass-produced models, combined with a steel or aluminum structure (Nehuis, et al., 2014).

The more common solution for achieving a lighter car body is by aluminum or steels with a higher strength. Aluminum has a light weight but a lower strength than steel and will require thicker constructions. Beside aluminum, a car-body includes high-strength (HS) and ultra-high-strength (UHS) steels. There are several advantages of using steels with a higher strength in a car body. Since higher strength enables a slimmer construction and thus a weight reduction through the reduction of mass. Steel is also preferable to use since they have a high energy absorption during an impact and enables fast joining methods and good formability (Kaščák & Spišák, 2013). The proportions of different materials Daimlers uses for the production of S-class is presented in Figure 9.

![Figure 9 – Material distribution in S-class, adapted from: (Kienzle, 2017).](image-url)
2.6.4 Joining in BiW Production

Joining in a BiW production is strongly differenced due to the high number of material combinations. Car-body manufacturers are using adhesive, thermal- and mechanical joining in a distribution seen in Figure 10. The methods in the group of thermal joining is preferable to use as a first option since the efficiency and flexibility is higher and the costs for each joint is lower (Boomer, 2006). Although, new material mixes forces manufacturers to use various methods. For instance, the profitable combination of aluminum and steel is yet only possible to join with thermal joining methods, such as resistance spot welding, arc welding or laser welding (Steegmüller, 2017). Table 1 describes characteristics for the main joining methods used in a BiW production.

![Figure 10 – Joining distribution in S-class, adapted from: (Michalak, et al., 2013).]
In this research, two of the most commonly used methods are chosen to integrate in a flexible manufacturing station. Resistance spot welding (RSW), which is a thermal joining method and self-piercing riveting (SPR) which is a mechanical joining method.

## 2.6.5 Resistance Spot Welding (RSW)

Resistance spot welding is used to weld together two or more metal sheets. Two electrodes with round tips, typically made of copper, squeeze the metal sheets with a certain pressure and conduct current through them. As a result, the material is melted together in between of the electrodes (see Figure 11). The power turns off when the spot is completed. The amount of energy delivered to the spot is determined by the amount of power and the duration of the power. These parameters are selected according to the material used, the thickness, the number of the plates and the type and size of the electrodes. If too much energy is released in the spot or if the force on the electrodes that holds the melt is too low, melted material spills out and creates spatter (Krsulja, et al., 2012). Thus, the quality of a thermal joining spot performed by a resistance spot welding gun is strongly dependent on three parameters: power, pressure and time (Omar, 2011).
RSW is mainly used for steel-sheet combinations, usually with a thickness of 0.5 to 3.0 mm (Todd, et al., 1994). Thick materials are difficult to weld because heat spreads in the material. Aluminum and stainless steel can also be welded. Aluminum requires more heat; therefore, the welding equipment must hold a high-power output and be able to build high pressure between the electrodes. Stainless steel requires lower temperatures but typically is not used in a BiW production (Kaščák & Spišák, 2013).

Heat input in a nugget performed by RSW is determined by the usage of Joules Law (Krsulja, et al., 2012), Eq. (2-1).

\[ Q = I^2 \times R \times t \]  
\[ (2-1) \]

Where:
- \( Q \) = quantity of heat [J],
- \( R \) = electrical resistance [Ω],
- \( I \) = current [A],
- \( t \) = time of current flow [s].

RSW can be performed manually or by a robot. Depending on the size and geometry of the assembly, welding can be done in a stationary tool, a handheld one or by a tool that is mounted onto a robot (Kimchi & Phillips, 2017). When a robot utilizes a stationary welding machine (Figure 12; right), the robot has a special gripper for handling the assembly and moves for indexing between welding spots. In contrast, the other alternative for an automated process is that the welding tool is attached to the robot (Figure 12; left). This is typically used in GEO operations since the assembly must be fixed in a fixture and the joining tool only has a small space for accessibility.
Tools that are mounted on a robot are generally designed in two main shapes, the X-shape and the C-shape. Figure 13 displays how the gun geometry differs between X-shaped and C-shaped welding guns. However, the geometry of the tool is strongly related to the geometry of the assembly. A car manufacturer must therefore hold numerous of welding guns with different geometries of both X-shape and C-shape for the joining of a car body (Daimler AG, 2018).

2.6.6 Self-Piercing Riveting (SPR)

Riveting is an alternative method for joining mix-material combinations in a car body. One advantage with the specific method of self-piercing riveting (SPR) is that it does not require pre-drilling. It is also possible to join multiple material stacks since the bondage is by an interlock function between the materials, instead of a fusion bond (Haquea & Durandet, 2017). Figure 14 display a cross section of a joint performed on a three-sheet material combination.
However, each performed joint consumes an element in forms of a rivet, which makes the method relatively expensive compared to RSW. Although, the SPR still has a superior mechanical strength, a tradeoff between cost and quality is always ongoing (Boomer, 2006).

The SPR process is executed in the following steps, shown in Figure 15: (1) the rivet is fed through a hose to the magazine of a riveting tool and placed in position. The tool presses the material against the die. (2) A punch inside the drive of the tool presses the rivet into the material stack. (3) The punch presses with specific forces until the bottom material has filled the geometry of the die profile. (4) When the bond is completed, the SPR tool retracts and the joint is finished (Haqua & Durandet, 2017).

There are various types of rivets available, as well several types of die profiles. The most common type of rivet to use in SPR is the semi-tubular (Danyo, 2014). The rivets can normally variate in flange thickness, length, size, diameter and hardness. The die profiles (see Figure 16) also variate on different factors. Mainly in diameter, depth and shape (Li, et al., 2017).
A combination of various rivets and dies leads to a high flexibility in the SPR process. Nevertheless, if there is no flexible solution of automatically switching between the set-ups within one tool, the flexibility decreases dramatically.

The SPR tool is rigidly C-shaped due to the high forces that is applied. The disadvantage with the rigid C-frame is the accessibility combined with a high weight. Joints that are located in the center of an assembly requires a long-reach C-frame for accessibility (Li, et al., 2017). Since the C-frame must be stiff, the tool will labor under a high weight. In turn, it will require a large robot for handling the tool. Additionally, when there is less accessibility to the part, the long-reach C-frame must be changed into a slimmer one for enabling joining. The result is that two different tool geometries are required for joining similar joint on one assembly.

2.6.7 Other Technologies used in a BiW Production

There are several technologies used in a station intended for car-body manufacturing. Some of them have been applied in a BiW production for several years. Following paragraphs include a short but comprehensive description of the function of a few basic technologies and tools.

Handling grippers

Handling grippers are devices for material handling operations. Handling grippers are normally mounted on an industrial robot for enabling a broader working range. Handling grippers are designed in two ways: welded or modular (Michalos, et al., 2015). A welded gripper consists of a welded frame with specific mounting points for clamping devices. The welded grippers are normally only able to handle one specific type of geometry. A modular gripper is generally assembled with universal and standardized aluminum profiles. The modular gripper can be rebuilt for another model. But the interface between the aluminum profile and clamping devices is normally not modular. Therefore, a lot of mechanical work requires to change the function of a modular gripper.
**Fixture tools**

Fixtures are means of production, in which the workpiece is fixed during the form changing performed in a manufacturing process. The workpieces can easily be positioned and clamped repeatedly onto the fixture. Fixtures are, in contrast to other resources, individually constructed to fit the geometry of the components that are executed (Trummer, 1994).

**GEO-grippers**

Geometry-grippers are normally combined with a fixture. GEO-grippers can either contribute with only additional clamping points to a fixture or handle single parts for holding them to an assembly in a fixture. The advantage with GEO-grippers is the ability for utilization of handling and fixture operations in one tool. The disadvantage is that GEO-grippers are normally relatively rigid and type specific. Consequently, a high number of GEO-grippers must be stored in a station.

**Industrial robots**

Industrial robots are flexible handling devices that use tools or equipment for manufacturing. The main function of an industrial robot is the ability to perform handling or process tasks in a producing facility. An industrial robot normally has 6 axes of freedom, therefore it is a common solution to mount the robot on a linear axis and so enable a 7 axes setup (Grote, 2014).

**Material logistics**

Material transports in a BiW production are generally performed by a chain conveyor or an Electric Monorail System (EMS). On such a system, parts are transported on an independent rail-mounted-vehicle (see. Figure 17) in a rigid sequence through the production line or between stations. The advantage of an EMS is that parts are transported along the ceiling and can therefore clear floor space.
Tool logistics

Exchangeable tools are used in a current production, mainly between a gripper and a joining tool or between different joining tools. The enabling technology is a common interface through a tool changer (see Figure 18). A tool changer holds the required connector elements, such as gases, fluids, power, signals and further options. There are special tool-storing stations developed for storing the tools close to the robot for a productive changing process in the station.
3 A Future Production of Car Bodies

Future changes due to developing propulsions, is among car manufacturers a frequently discussed question. Several projects have been launched to meet the future changes in the industry. Some of the projects are still conceptual, and others are realized. This chapter deals with incentives for change and how Daimler encounters and adapts to it with their internal projects. In addition, external projects that are directly related to car-body manufacturing described as well.

3.1 Statistics in Production of EV

Production of electrical vehicles worldwide is continuously increasing. In 2011, the percentage powertrain units for EV was 0.12% of the production share. Currently, for 2018, the percentage has increased to 0.55% of the production share. Projected, this number will continue to increase to 0.62% in 2020 (KPMG; LMC Automotive, 2017). During the second quarter of 2017, China was ranked as number one country in the total field of electromobility. Close behind follows the U.S. with approximately the same numbers as China. Germany is then placed in third place. The field of electromobility can be divided into: Industry, Technology and Market. China and U.S. qualify on top because of a large industry and market. However, Germany is rated twice as high in the technology area and can so overtake both China and U.S. by an increased market and industrialization in the area of electrification (Berger, 2017).

3.2 Daimler’s Approach for Electrification

Automotive industry is growing towards electrification of cars. New models are rising, and current ones are updated as electrified alternative. Daimler has invested in a program for their brand Mercedes-Benz. Electric Intelligence - EQ is a new product and technology brand that has arisen with this investment. Daimler will invest 10 billion Euro in the EQ program and another 1 billion Euro in battery production during the coming years. These investments follows a launch of up to 50 variants of EV in Daimler’s model portfolio from year 2019 up to 2022 (Mercedes-Benz, 2018). The aim is to provide an EV in each of the current available model series. A minimum of 10 variants will be offered as fully electrical (BEV) by 2022, and the goal is that the body of new vehicles can be produced together with internal combustion engine vehicles (ICEV) in one line (Krust & Krugsberger, 2017).
3.3 Challenges for the Production of Car Bodies

Today’s market does not only require car manufacturers to have a large portfolio of models and associated derivatives. There is also a need for alternative propulsions. Hybrid and electrified vehicles conspire a certain product complexity due to new materials, combined with a complete new architectural design for batteries and electric engines. This forcing car manufacturers to develop production systems that can adjust for a quantity volatility without a rise in factory footprint. New materials and geometries requires technologies for a sustained, or increased, flexibility in a production system (Attias, 2017).

As a result, a flexible production system must handle changes in all of the areas described in previous paragraph and visualized in Figure 19. To reach full changeability, the production system must handle the market changes that forces new models, in different variances, with different propulsion alternatives, which requires new materials in the car bodies, into a manufacturers current portfolio.

Figure 19 – Challenges for the production of car bodies (Daimler AG, 2016).

The conclusion is that today’s production systems are not prepared for the increased variances that may arise. It is essential to develop production systems that can adjust for an alternation between products in a current portfolio, but also with the opportunity to integrate new ones.
3.3.1 Car-Body Classification

A model of a car is not engineered as one type of body style, size or capability. Normally a model can be built and offered in several derivatives. For example, a four-door sedan, a five-door station wagon, a folding-roof cabriolet, a two-door coupé or even as a sport-utility vehicle (SUV). Commonly, manufacturers strive to utilize assemblies in a modular way between derivatives, to be able to have a large portfolio to a worthwhile cost (Haajanen, 2007).

A successor is when a model of a car is updated with completely new geometries and materials. A facelift of the current model is normally launched before the successor comes. A successor is routinely produced in a completely new production system and for that reason they are also demanding lots of resources during introduction (Haajanen, 2007).

A new model is one that is not in a manufacturer’s ordinary portfolio. A new model has less similarities to design- or construction of another model in the portfolio (Haajanen, 2007). The propulsion often affects the type of construction a car requires and may therefore be a reason for the arising of a new model.

In Figure 20, the connections between a current and new model series, derivatives and successors are illustrated with examples related to the classification of Mercedes-Benz Cars.

![Figure 20 – Daimler’s model structure.](image)
3.3.2 Architectures of Mercedes-Benz Cars

The numbers of models produced by Mercedes-Benz Cars are divided into several groups with respect to the platform architecture. Except from the special vehicles, such as the G-Class or the AMG GT, there are four main-groups of architectures. The MRA (Rear-Wheel Drive Architecture), MFA (Front-Wheel Drive Architecture), MHA (High Architecture), and MSA (Sports Architecture). The group of MRA includes all the rear-wheel-drive models of the passenger cars. MFA is the group of vehicles with front-wheel drive. The group of MHA contains the models produced on a platform as high-wheeler/off-road vehicles or in other terms, SUVs. Finally, the MSA-group contain the platform for sport vehicles, with a severe weight reduction by usage of aluminum together with carbon fiber reinforced plastic (Kurylko, 2014).

Figure 21 illustrates the propositions of models in each group of architectures. The group of MRA vehicles has currently the largest share of vehicle models within the same architecture and are therefore a reasonable group to study in this research. If a flexible station can produce all models within the largest group of vehicle architectures, it can also be applicable on the remaining groups. The architecture of vehicles with an alternative drive will have an increasing number in the coming years, and the vehicles in that group can therefore be considered as new models in this project (KPMG; LMC Automotive, 2017).
3.4 Flexible production in the plant of BMW

The car manufacturer BMW AG has approached the production problem, with an increased portfolio of car-body types, by maintaining flexible production systems in their plant. BMW utilize a common production system for the production of major subassemblies such as engine compartments, mid-floors, rear-floors and side-bodies. The production system has the flexibility to handle subassemblies for both the 1-series and the 3-series. Flexibility in robotic automation is today highly developed in the production systems. Therefore, a high model-flexibility is provided by flexible tooling procedures together with a common design of subassemblies. BMWs stations itself contains tools that either are adjustable for different geometries or commonly designed for a number of variants (Kochan, 2005).

Mobicell is a station concept that BMW developed for the production of subassemblies. The principle is that the station can be moved from one plant to another and have the production running just within a few days. The benefit with mobicell is that any type of derivative can be produced in different volumes at any BMW plant. This is advantageous while the start and end production of a model is not the same at every plant (Kochan, 2005).

3.5 Daimler Car-Body 4.0

Daimler has a continuous pursuit of having a connected and interconnected car-body production. Within development of Mercedes-Benz Cars, this is achieved through conceptualization and realization of production systems in the global project Daimler Car-Body 4.0. The research in related projects is carried out by the department TECFABRIK, which works for production and supply chain developments towards Industry 4.0 (Huber, 2016).

Related to the general direction of Industry 4.0, Daimler strive to find advantages in following subjects (Huber, 2016):

- Shortening of start-up times.
- Reduced procurement times for production facilities.
- Optimization of the production and the assembly processes.
- Increased level of automation through human-robot interaction (HRI).
- Flexibilization of the production by versatile production systems.
- Global optimization of production processes.
Directly related to the production of car bodies, Daimler adapts to product changes by improvements in the production systems and following topics (Huber, 2016):

- Greater flexibility in a system for producing increasingly complex products.
- Increased efficiency through a constant use of available resources including energy and the optimization of single technologies.
- Flexible high-speed production systems with a fast commissioning of new plants.
- Safe and attractive workplace and consideration of demographical changes.
- Smart logistic system from demand through production and delivery.

Through these goals, Daimler aims for an interconnected and profitable “smart factory” for the production of car bodies in a future scenario.

### 3.5.1 CubeTEC – Versatile BiW Production Concept

The project CubeTEC is a production concept for maintaining feasible solutions in having short-term model cycles, an increased model diversity and to meet the challenges of electromobility. In TECFABRIK, a pilot module (see Figure 22) has been built up to demonstrate the advantages of a versatile production system (Krust & Krugsberger, 2017).

![CubeTEC pilot module in TECFABRIK (Daimler AG, 2017)](image)

Due to the high flexibility in a CubeTEC station, several derivatives within a model series can be manufactured in a shared number of stations. Today, this requires several model-dedicated production lines. A production system as CubeTEC can be used to produce car bodies for vehicles with an internal combustion engine as well as for battery-electric models that require a modified basic architecture due to the battery.
Single body parts in a traditional car body are assembled in a rigid production line by various processes, such as welding and self-piercing riveting. In CubeTEC, individual stations are set-up and separated with respect to the process. Each station has a high flexibly and several stations are connected to one another via a driverless transport system.

Generally, a CubeTEC production differentiates from a conventional line by the separation into three submodules, shown in Figure 23. Within the first module, logistic of single components and subassemblies are organized at a common area. The second module is focusing on the processing of geometry operations required to form a subassembly from single parts. Finally, in the third module, respot joining is carried out for the finalization of a complete subassembly.

By the separation of logistics and the joining processes together with driverless vehicles, CubeTEC realizes benefits of bounded logistic operations together with a forklift-free production. Furthermore, CubeTEC has a high derivative flexibility due to a simple duplicability of stations. Additional stations can be added for additional volumes of derivatives in a model series. Beside a high process flexibility, rework- and measurement stations, as well as systems for component logistic, can also be utilized between CubeTEC stations.

A conventional line consumes a great amount of factory floor by the usage of rigid steel constructions together with large part buffers at each station. CubeTEC has a logistic system that utilizes a Supermarket instead of relatively inflexible LCAs that are placed at each station. By this change, CubeTEC can reduce the footprint of a production system in a BiW production plant. CubeTEC combines state-of-the-art techniques together with modern techniques. In the pilot module of CubeTEC, new and adaptable tools are tested and compared to conventional ones. Lightweight materials are tested in constructions such as tools and fixtures. A weight reduction in tools for handling operations can enable downgraded robot classes and consequently bring lower investments.

![Component Logistics](image1.png) ![Geometry Joining Station](image2.png) ![Respot Joining Station](image3.png)

Figure 23 – Separated submodules in a CubeTEC production (Daimler AG, 2016).
3.5.2 Component Logistics

Following differences in component logistic between a conventional production system and a versatile production system as CubeTEC are identified:

**Logistic in a conventional production (see Figure 24):**
- Rigid arrangement of parts.
- High space requirement for individual parts around the plant.
- Parts arrive at the plant with forklift.
- Limited options for integrating a new variant

**Smart logistic in a Supermarket (see Figure 25):**
- Parts logistics via AGVs.
- Clear logistics structure, no mixing with production area.
- Variant-flexible parts provision.
- Forklift-free production.

*Figure 24 – Material supply in a conventional production system (Daimler AG, 2016).*

*Figure 25 – Material supply from a SM in a modular production system (Daimler AG, 2016).*
3.5.3 Geometry Joining Station

Following differences in geometry operations between a conventional production system and a versatile production system as CubeTEC are identified:

**Geometry procedure in a conventional production (see Figure 26):**
- High number of robots without variant flexibility in a rigid arrangement.
- Large, solidly bolted fixtures.
- Limited options for integrating new variants.
- Material is stored around the plant with little buffers.

**Geometry procedure in a flexible GEO station (see Figure 27):**
- Clever arrangement of robots with flexible grippers for different assemblies.
- Type change possible in cycle time.
- Successor flexibility through interchangeable grippers for the robot.
- Modular principle of grippers and fixtures.

![Figure 26 – Geometry procedure in a conventional production system (Daimler AG, 2016).](image1)

![Figure 27 – Geometry procedure in a flexible GEO station (Daimler AG, 2016).](image2)
3.5.4 Respot Joining Station

Following differences in respot operations between a conventional production system and a versatile production system as CubeTEC are identified:

Conventional respot arrangement (see Figure 28):
- High density of robots without derivative flexibility in a rigid arrangement.
- Specified joining sequence, change of order for another variant is not possible.
- Mix of joining technologies and the utilization are vehicle related.

Modular respot station (see Figure 29):
- Clever arrangement of robots with flexible grippers for different assemblies to be joined.
- Maximum utilization of the respot station through free access to required joining technologies.
- Respot processes secluded from GEO stations.

Figure 28 – Conventional arrangement of respot robots (Daimler AG, 2016).

Figure 29 – Modular respot station (Daimler AG, 2016).
3.6 Project: SmartBodySynergy

SmartBodySynergy (SBS) is a project subsidized by Bundesministerium für Bildung und Forschung, in which a number of partners are involved. The main objective with SmartBodySynergy is the development of a process for integration of electric vehicles in a current production. A solution to this is a modular joining station, as a submodule to an existing or future production (Kupzik, et al., 2018). Through a high modularity level, and with the possibility to change tools and necessary equipment for producing alternative architectures, follows a high grade of flexibility within the joining station.

3.6.1 Work Packages

The project is divided into five work packages (WP) with different subject areas. Each one of the involved partners is responsible to fulfil research in a respective assigned WP.

In WP 1, which mainly concerns the research in this report, the goal is to conceptualize a modular and highly flexible joining station. This includes layouts, cycle time analyses and logistics on the in- and outside of the station. The flexibility within the station is realized by plug & produce-compatible gripping and clamping systems together with interchangeable joining tools. As part of a conceptualization and realization, the key technologies that are developed in WP 2 and WP 3 will be integrated here (KIT, 2016).

The aim of WP 2 is the development of flexible and plug & produce-compatible handling and joining equipment. Due to different materials and thicknesses of the sheets to be joined, the joining tools often has to be changed and kept in the station. The plug & produce-compatible joining tools to be developed for this purpose must be able to communicate independently with the robot and be ready for use without further manual steps. This requires the use of common interfaces and communication standards, which represent preparatory work for standardization (KIT, 2016).

Focus in WP 3 is to develop intelligent quality-assurance technologies that allow a complete inspection of all quality-critical characteristics of respective part. In addition, a dynamic measuring technology should be feasible and future tests anticipated (KIT, 2016).
WP 4 contains research of a decentralized control- and logistic concept including the management of AGVs and material flow in a modularized production. A simulation is used to design the material picking zones and to determine the number of AGVs needed together with the required lead time for the supply chain (KIT, 2016).

In WP 5, a tool for an economic evaluation and an implementation strategy of modularized production systems is included. This work is based on a simulation that simulates the optimal production mix and stations linking with the aid of AGVs. On the basis of simulation studies, an action guideline is compiled, which can be applied comprehensibly and standardized to individual submodules in a production system (KIT, 2016).

### 3.7 Flexible Systems for Car-Body Manufacturing

An increased diverseness of vehicle variants in the automotive industry is a fact. Therefore, systems for sustaining a flexible production are continuously developed in the BiW area. New systems are not only in-house concepts developed by car manufacturers, but flexible systems are also developed through research projects and by subcontracting companies. The subcontractors strive to sustain an objective view of BiW manufacturing and to deliver solutions and concepts for plug-n-produce.

#### 3.7.1 Migration Manufacturing

A solution concept for the short lifecycles together with a rising model portfolio was presented by Meichsner. The Concept is called Migration Concept and refers to a solution which holds a high flexibility between the production of several models and derivatives. The principle is to deprive the mindset of line tact and line balancing and instead focus on scalability and the work content.

The Migration Concept was described by (Meichsner, 2009) as:

“Migration (from the Latin for “move from one place to another”) refers in this context to the technological modification or transformation of all or parts of a production system (e.g. of vehicle body lines) at a manual, semi-automated or highly-automated level, with the possibilities that this offers, in terms of the growth, division, partial or complete consolidation of capacity, and/or reduction of a plant system.”
In Figure 30, three principles of manufacturing are shown. Both the single-line and the flexible principle are developed for long lifecycles. However, the Migration concept can enable short lifecycles in a production of various models together with additional derivatives.

The basic concept is developed from the available flexibility types in a car-body production. The flexibility types are shown to the right in Figure 31. To the left in the same figure are also the changeability enablers displayed. The changeability enablers are the keys for a complete versatile production where production can be changed between several models and derivatives.
The Migration Concept is based on two types of layouts: Meandering and Tetris. The Meandering layout, shown in Figure 32, consists of a main line with geometry stations. Respot lines are then meandered out from the main geometric line. In the main line, all geometry-forming devices are placed. An increase in the capacity can be realized simply by adding a respot line to the main geometric line. The respot lines consist of standardized components, e.g. robots and welding guns. The investment and reaction times to implement an additional welding line are therefore low. Instead, a change or addition of a model takes place directly via the intervention in the geometry main line.

The Tetris layout concept in Figure 33 utilizes a system for interconnection between single geometry- and respot stations. When increasing the number of units or integrating additional models, individual stations are switched on. Investments are phased in by adding more cells. Model changes are easily enabled since only individual stations are affected by the changes, and not the entire system.
3.7.2 KUKA Matrix Production

KUKA’s solution for maintaining a high level of flexibility is their Matrix production system. The production layout is divided into several cells containing a number of robots and turntables for tools. As seen in Figure 34, KUKA strive to separate logistics from production. Together with the cells, the concept depends on a warehouse for the workpieces and a tool store for storing the tools required for a specific operation. Material- and tool supply to each cell is solved by having transportation performed by AGVs. Each cell is built for an AGV to drive straight through the station, with an entrance- and exit gate (Reuter, 2016).

At first, an AGV receive a work order to drive to a cell with the workpiece or the necessary tools. In next step, the robot, at a station, pick the part up and start processing. KUKA exploit their already intelligent robot applications for handling and joining in team of robots (Reuter, 2016).

The Matrix concept can adapt the production according to fluctuations in demand. If the demand of a particular model increase, new cells can be added and if the volumes decrease, cells can easily produce another model. The value chain will not be interrupted if any of the cells would have disturbance. The versatility of the concepts is that processes can run independently and a modular expansion of the cells in the matrix layout enables easy integration of new products (Reuter, 2016).

![Diagram of KUKA Matrix Production](image-url)

*Figure 34 – Concept Layout of KUKA Matrix Production (Reuter, 2016).*
3.7.3 ComauFlex

ComauFlex is a flexible and modularized manufacturing system for the production of main- and subassemblies in BiW structures, developed by Comau. Comau describes the advantages of ComauFlex in a random-sequence production scenario where various material combinations can be joined with diverse joining methods (Comau, 2018).

ComauFlex is divided into two systems shown in Figure 35, VersaRoll and VersaPallet. VersaRoll is mainly used for geometrical joining of larger subassemblies, such as underbody- and side body. In VersaRoll, several modular stations can be combined to gain the desired configuration of joining sequence (Webster, 2015).

VersaPallet on the other hand is a tooling pallet that moves the car body through the production line. VersaPallet has the flexibility to change between tooling pallets and therefore also be able to handle a mix of models. The applications for VersaPallet is typically assembly of complete underbody or framing of a car body (Webster, 2015).

A combination of the two modules ensures a flexible BiW production with a high precision. One of ComauFlex’s advantages, compared to similar systems, is the utilization of floor space. To save space, most number of joining robots are mounted in a frame directly above the station and enables full accessibility to the part below. Since the system is modular, an expansion can be provided in a short time frame and to a lower risk than a conventional system. ComauFlex enables model-flexibility, high volumes and flexible cycle times (Webster, 2015).

Figure 35 – FlexCell as VersaRoll (left) and VersaPallet (right) (Comau, 2018).
3.7.4 FlexCell ThyssenKrupp

ThyssenKrupp System Engineering’s FlexCell is a modular system for flexible manufacturing. The possibility to combine several modules results in a highly adaptable production, the combination can either be planned as simple or complex. In Figure 36, a combination of three FlexCell modules is shown. The modular FlexCell can be combined as an individual line for subassembly parts, but it is also possible to combine modules for final assembly, for instance, hang-on parts (ThyssenKrupp, 2017).

FlexCell is configured upon customer’s request of e.g. robot type, joining method and fixture or position table. The modules are prefabricated at ThyssenKrupp System Engineering and can easily be moved with a forklift to another position or location. FlexCell is ideal for test series or prototype construction, as well for series production (ThyssenKrupp, 2017).

The FlexCell concept is designed for high adaptability, which enables flexible production at changing locations as well as material flow optimization through rapid relocations (ThyssenKrupp, 2017).

Figure 36 – Modular combination of FlexCell from ThyssenKrupp (ThyssenKrupp, 2017).
3.7.5 ABB ModulFlex

ABB has developed ModulFlex, a production concept for the production of several variants of subassemblies or body sides in one BiW-manufacturing station. A ModulFlex station utilizes a fixed number of robots in cooperation with a modularized and expandable system for swapping the fixtures between variants. Several model-dedicated fixtures are placed on a linear axis and can be driven in and out of the working area of the station. ModulFlex is a modular system so that platforms for fixtures can be added to the system, and therefore enable a production of an extended range of product variances (ABB, 2018). The expandability is gradually described to the right in Figure 37.

Since platforms with fixtures are driven into the station, parts can be loaded in a robot-free area and enable either a manual or automated loading of parts into the fixture (ABB, 2018).

The basic configuration, seen to the left in Figure 37, is designed for six platforms with a changeover time of 12 seconds. The arrangement also includes up to 4 joining robots in each station. One of the main advantages with ModulFlex is the easy integration of future geometries, since the dedicated fixture on the platform can easy be changed parallel to productive time of a station (ABB, 2018).

Figure 37 – ABB ModulFlex isometric view (left) and station expandability (right) (ABB, 2018).
4 Method of Investigation

The conversion of primary data into practical theory was based on the methods described in this chapter. The study originated from a need to improve the ability of a manufacturing station to alternate the production between numbers of car models in a current or future portfolio. The manufacturing station could be able to produce independently, but a primary target was to have it integrated in a current production scenario.

The procedure for tackling the problem statement and answer the research questions described in Chapter 1 and illustrated in Figure 38 was to:

1. Investigate the differences in a car-body production designed and constructed for high flexibility, compared to one developed for high volumes.
2. Set up different cases representing the challenges in a production. Determine how the challenges compels to changes.
3. Perform investigations to supply a number of concepts in which the target was to compare the capacity, changeability and footprint of the proposed concepts.
4. Determine whether an MFG station is beneficial and can be integrated in a production.

![Funnel for method of investigation](image)

4.1 Production Scenarios

The research in this report considers how to achieve flexibility and efficiency in the current industry of BiW production. The initial part was to create an understanding by study how design and layout of a new production system can be compared with a current one. Since BiW production is a wide research area, the study was set to be on a structural level and not narrowed down into detail. To understand where and when a new production system is beneficial, underlying strategies in car-body production were studied, as well as how the market effects a BiW production.
At first, several production scenarios that defines a current and future states of a car-body production was described. Generating production scenarios was performed for gathering already available technologies and how technologies installed in an MFG station could interact with those during an integration case. Since an MFG station was not destined to be place in the intermediate vicinity of a production system, logistic between a current production and an MFG station was a crucial part to describe during the generation of production scenarios.

### 4.2 A Case Study of Challenges

From secondary data gathered during the literature review, several cases were outlined with respect to those changes a car-body production must encounter in the future. The cases were broken down into subcases for the analysis part and were essential for determine potential situations where an MFG station can be integrated.

### 4.3 Concept Generation

Since a concept of an MFG station was already generated, it was further analyzed with respect to applied technologies and flexibility-enabling factors. After the analysis of the current concept, a technology table with already implemented technologies and new ones, was created. The technology chart included technologies that define a certain changeability within a manufacturing station or line. From the technology table, a morphological analysis was performed to combine technologies in a number of MFG concepts with respect to the total level of changeability. The changeability was measured with respect to the process and to the logistic in the station.

In addition, a cycle time analysis for each MFG concept was performed in order to determine the capacity of respective station. Furthermore, layouts were drawn to demonstrate the arrangement of hardware and to calculate station footprint.

### 4.4 Production Interaction

The interaction analysis was performed after the MFG station concepts were generated and compared. It included challenges in technologies and logistics if an MFG station is integrated into one of the respectively production scenarios that are described in Chapter 5.
5 Generation of Production Scenarios

Upcoming car production is facing new challenges due to new and different models. Flexible systems are developed, and in some areas integrated. Daimler AG is facing two major scenarios in the future of BiW production. Therefore, it is necessary to develop more than one concept of an MFG station depending on the current production scenario. This chapter describes realistic production scenarios that a concept for an MFG station may encounter.

Before explication of a detailed concept regarding an MFG station, it has to be decided which type of production scenario an MFG station will encounter in the future. The production of car-bodies can appear in different scenarios depending on the type of production system. In this research, it is chosen to separate the production scenarios into two possible situations that are shown in Figure 39. The first is in a Brownfield area, where the production concepts already are implemented in today’s production. The second situation is a Greenfield area with totally new concepts for a car-body production. The goal is to find in which one of the scenarios an MFG station can prove itself beneficial for integration of a new model. In the situation where the concept of an MFG station, for practical reasons, does not allow an integration, it is explained why it will not be advantageously. The Brown- and Greenfield scenarios were chosen to be separated based on a current production, versus a production in development stage.

![Figure 39 – Flowchart for integration of an MFG concept in a production scenario.](image-url)
5.1 Production Scenario 1 – Brownfield

The integration of an MFG station in a Brownfield area requires a number of aspects to take into account due to the existing limitations in the system. Before an integration, consideration should be given to the fact that the production system is producing daily and can therefore be ruinous to shut down for a longer period of time. In a Brownfield area, there are production scenarios that can lead to a situation where an MFG station cannot be integrated.

5.1.1 Scenario 1.1 – Conventional line

Production of car bodies in today’s conventional system differs from a modularized production system. All of the production steps are integrated into one line with sequenced operations from beginning to end. In short, the conventional line layout is product-oriented with subsequent steps of GEO and RS operations in one rigid line. The joining and handling equipment are customized for the type-specific models that are manufactured in one line. Hence, the system requires a certain volume of in-line buffer to handle production stops during maintenance or in case of a breakdown. Otherwise, the whole line cannot produce any assemblies. As seen in Figure 40, materials are stored in the direct vicinity of the production line and mixes production with logistics.

![Figure 40 – Conventional production line (Daimler AG, 2017).](image)

Material supply in a conventional logistic system is handled in two different ways depending on the size and weight of the part. Larger components are handled by a robot in an automated process. Therefore, they need to be loaded in a specific way to enable accessibility of the handling gripper. This is done via a custom-built storage rack for automotive components (SLT), shown in Figure 41. Each contact point between the component and the rack has a well-defined geometry for maintaining high accuracy of positioning the part for the automated handling.
Small components, that are within the size and weight of being manually manageable are loaded in a *universal storage box* (ULT), shown in Figure 41. Each box can store a number of components stacked on each other and does not have the drawback of transporting volumes of air in between the parts.

The transportation of respective storage container is done by a forklift, tugger train or similar vehicle due to high weight. Each storage container is delivered directly next to the operation which processes the transported parts.

![Figure 41 – SLT (left) and ULT (right) (Davco Industries, 2018).](image)

### 5.1.2 Scenario 1.2 – CubeTEC Light

CubeTEC Light derives from the principle of CubeTEC, which was described in Chapter 3.5.1. CubeTEC Light is a semi-flexible production system with a separate loop for material supply via a Supermarket. The connection of the supermarket to the individual dispensing and receiving points at the stations takes place via a driverless transport system. The connection from station to station takes place via a conveyor system.

The production flow is based on having a semi-flexible geometry station, directly followed by a respot station with mixed joining techniques, integrated into one combined station. A mixed respot station has all the operations that are necessary after one geometry station. CubeTEC Light, shown in Figure 42, has completely separate production stations for the engine compartment respective the rear floor.

CubeTEC Light relies on material supply via a supermarket, where single parts are loaded both manually and automatically. Large and heavy parts are handled by a robot. While smaller, more manageable parts, are handled manually by a worker. The distribution between an automated- and manual handling process is equally divided.
From the supermarket, parts are delivered to the joining area by a number of AGVs. Each AGV consists of the number of parts that are required for one car-set. When the AGV has reached the first geometry station, the platform that contains the single parts, is separated from the AGV. The AGV then returns to the supermarket for transporting the next car-set. Simultaneously as the AGV returns, the first geometry station is performing joining of single parts to one compounded assembly.

The material flow between a geometry station to a respot station, and forward to the upcoming geometry stations, is done by a conveyor system. As a result, the production line becomes rigid after the platform is detached from the AGV. Consequently, one significant part of the flexibility, to run another route between stations or overtake another AGV, is lost. This type of production has a number of drawbacks in terms of flexibility, similar to those that can be observed in a conventional BiW production line. That is because CubeTEC Light processes a predetermined sequence of parts.

![Figure 42 – Layout of CubeTEC Light (Daimler AG, 2017).](image)

**5.2 Production Scenario 2 – Greenfield**

Scenario 2 is a production plant completely build from scratch without any conditions or obligations to the existing production form. A complete Greenfield project in which the focus could be production of a derivative, successor or a new model, such as an EV. The production scenarios in a Greenfield area are not implemented yet. Therefore, it continuously changes, which can benefit or hinder the integration of an MFG station.
5.2.1 Scenario 2.1 – CubeTEC Light+

CubeTEC Light+ is a not-yet developed production concept that could occur in the paradigm shift between already implemented, semi-flexible CubeTEC Light, and a fully flexible CubeTEC. In CubeTEC Light+, the geometry station and respot station is still integrated into one combined station, as in CubeTEC Light. The difference is the logistics. The material flow in a CubeTEC Light+ production scenario is managed by AGVs and has therefore the advantage of full flexibility in sequencing. As seen in Figure 43, an AGV can go directly from combined station 1 to combined station 3, without having to wait in sequence for combined station 2 to be finished.

However, this enables a high level of logistical flexibility and transports between stations, but not yet full flexibility within each combined station. The respot operation in a combined station can only be performed on assemblies within the same family (rear floor or engine compartment) and not both.

Figure 43 – Layout of CubeTEC Light+ (Daimler AG, 2017).

5.2.2 Scenario 2.2 – CubeTEC

CubeTEC Full Version is a production concept with the ability to produce subassemblies, like rear floors and engine compartments, in separate geometry stations but with a shared number of respot stations. CubeTEC is the foundation for a versatile production system, and the advantages are described in Chapter 3.5.1. Previous explained scenarios derives from the full version of CubeTEC.
The starting point is a supermarket. Here are all necessary parts for the different models, their derivatives and successors, are provided centrally. Required parts are no longer in the immediate vicinity of the production. In a first step, these are delivered to a GEO station via AGVs. In the GEO station, the individual parts of the engine compartment or rear floor are brought into the correct position and finally fixed so that the resulting modules and components can be further processed. A GEO station with an adjustable fixture keeps the individual parts in the desired position so that they can be fixed geometrically by welding robots. The adjustable fixture makes it possible to automatically process components of different geometries.

The logistics is divided in two separate AGV loops, illustrated in Figure 44. The first loop contains transports of single-part car-sets from a supermarket to the geometry stations. A second loop includes transportations of geometrical joined subassemblies between the geometry stations and the respot stations.

The center of Figure 44 displays the respot stations that are placed together in a respot area. To get full flexibility in the respot area, the respot stations are sorted by joining processes, such as RSW aluminum, RSW steel, SPR, Clinching, FDS, etc. The sorted respot stations are able to handle an eventual breakdown in one or more of the stations without interrupting production takt. By using multi-purpose grippers, each station has the flexibility to join both rear floors and engine compartments.

In CubeTEC, additional GEO stations that might be required for a new model, derivative or a successor, can be added to the system and therefore utilize the already existing respot stations.

Figure 44 – Layout of CubeTEC (Daimler AG, 2017).
5.3 Logistics in the Production Scenarios

Except for the technical aspects in the four scenarios, there are also significant differences in the logistic flow between the production types. Figure 45 illustrates the work stations in respective production system and the logistic flow related to them. The dashed lines in Figure 45 discloses the material flow of single parts, delivered directly from a warehouse or from a supermarket. The solid lines describe the logistic flow from one work station to another.

In a *Conventional Production*, single-parts are delivered on a SLT and ULT (described in 5.1.1) directly from a warehouse to the GEO operation by a forklift. The subassembly is transported within the line by direct-delivery or by conveyor systems. In a conventional system, logistic and production are mixed in one line.

In *CubeTEC Light*, a conventional system has been separated into combined stations containing GEO+RS. The subassembly is transported in sequence between the combined stations. In addition, the single-parts are delivered as a car-set on an AGV to the first GEO station, and follows the subassembly through succeeding stations. The car-sets are arranged in a supermarket (5.3.2) Therefore, the material logistic and the production can be considered as separated.

*CubeTEC Light+* follows the same strategy as *CubeTEC Light*, by having combined stations for processing and separate material supply of single parts from a supermarket. Nevertheless, the logistic flow of subassemblies differs between those combined stations. In *CubeTEC Light+*, the transports between stations are not in a fixed sequence and are so enabling a higher level of flexibility.

In *CubeTEC Full Version*, the GEO and RS station are separated from each other for an even more increased level of flexibility. Compared to *CubeTEC Light*, the material supply of single parts and the logistic of subassemblies between the stations, are by two separated AGV loops. One AGV loop contains only single-part deliveries between a Supermarket and a GEO station. A second loop contains only transports of subassemblies between GEO stations and RS stations.
5.3.1 Material transports

Material transports in CubeTEC, Light+ and Light are executed by AGVs attached to a trolley that carries a platform with parts. An RFID chip is attached to each platform to ensure unambiguous identification within the system. The data carrier is coded with the vehicle identifier (body number + TMU). The platform is connected firmly to the AGV via a mechanical function. The platforms have the necessary flexibility to be able to record all parts of the ICEV as well as the EV in a defined manner. In this way the components can be safely transported and reliably picked up by respective handling robots and delivered to the geometry stations.

In CubeTEC Light, the components, and later produced assemblies, are transported on the same platform from station to station. Unlike the logistics system in CubeTEC, where single parts and assemblies are transported on separate platforms. The components on the platform do not project beyond the base plate of the component holder. During automated loading, the robot must position the components exactly on the platform. The platform has the same accuracy as today's loading systems (e.g., LCA). The loading of the platform is done manually and automatically, but the unloading of parts is carried out exclusively automatically.

5.3.2 Manufacturing Supermarket

The supermarket (SM) fulfills the purpose of a sorting function, to unstack ULTs and sorted SLTs so that a predetermined production sequence can be formed. In a supermarket, parts for different models or derivatives can be stored in one place for a clear overview.
The main purpose of the supermarket is the automated and manual picking of components to load the platform within a defined sequence. In the supermarket, illustrated in Figure 46, the AGV first enters the picking station for the manual loading of the platform, and then the picking station for automated loading.

![Supermarket Diagram](image)

*Figure 46 – A principle of a Supermarket (Daimler AG, 2017)*

### 5.3.3 Sequencing and Balancing

The planning department uses a main system for generating an optimized sequence of producing cars to meet the demand, a so-called Master Sequence. This is the sequence in which car bodies need to be delivered to the next station, but it does not require the station itself to produce in this sequence. Therefore, each subassembly production has a separate system for generating a new sequence that is optimized for each line- or modular scenario. The key of having separate sequencing systems together with a main system is that each subassembly system can manage to deliver assemblies in the given Master Sequence for the subsequent steps.

The ability to produce an assembly in an alternative sequence is limited. Metal sheets overlap each other on a certain level and must therefore be assembled in a certain sequence. Geometrical joining of single parts is performed before respot joints. That order is not interchangeable. Though, balancing of stations can be done by “transferring” joints from either GEO operation to RS operation or in opposite direction. E.g. A high number of joints are performed in an RS station with a cycle time that overrides the boundaries. The preceding GEO station is performing a less number of joints, but still with a cycle time within the takt. As a solution, it could be possible to perform more joining in the GEO and less in the RS to balance the workload.
6 Challenges from Changes - A Case Study

In this chapter, a number of cases that can occur in car-body production are generated and described. The cases contain challenges that may arise due to changes. Furthermore, one case with several subcases is chosen for a more in-depth analysis of problems and potential solutions.

6.1 Case Generation

Political and personal alterations are affecting the market for automotive industry. It forces car-body manufacturer to have a wide range of vehicle variants with different options of propulsion. A new vehicle architecture does not only increase the manufacturer’s portfolio, it comes with a lot of production challenges. To conceptualize and declare the advantage and an MFG station, the first step is to see the production from several perspectives. An MFG station may, in the correct planning, fulfill the integration of a new vehicle in an existing production. But an MFG station can also be of advantage in cases when a current production has disorders or fluctuations. To explore the challenges an MFG station may encounter, three cases have been created. Each of the cases in Figure 47 argues for a specific event and deals with a potential problem.

6.1.1 Case A – Production of a New Vehicle Model

Case A discloses the available options when a new model, derivative or successor is launched and integrated in a production. The integration is related to a systems new product flexibility described in Chapter 2.1.2. A general question during the generation of Case A is whether the production will be executed in a Greenfield or Brownfield scenario that was described in Chapter 4. The different options for producing a new model in a production can be listed as:
A.1 New production system
If the production of a new model, derivative or a successor, is projected to be at a high volume from start, an MFG station may not be necessary to implement. The high-volume model is best suited to produce in a highly flexible production system (CubeTEC, Light+) or a production system with lower-flexibility (conventional line, CubeTEC Light). The advantage of starting the production directly in a highly flexible production system is when the subsequent model of the successor is launched. Then the flexible system can be partly reused during a second lifecycle.

A.2 Independent MFG station
If an MFG station is implemented in a Greenfield scenario, it can be either integrated in the current material flow, or not. When an MFG station is integrated in a Brownfield scenario, the possibilities to have a shared logistic between an MFG station and the production, are limited. Therefore, one alternative is to set up an independent MFG station with combined respot operations. It enables an MFG station to process all geometrical steps of a low-runner, test series or prototypes in one station and thus minimize footprint and transportations. An MFG station will in such case act as a separate production system, but with a lower output than a conventional line or modular system. If an MFG station works independently, it can produce in parallel with any type of production system.

A.3 MFG station for all new-model GEO-steps
Case A.3 discloses an MFG station that is logistically connected to the respot stations in a flexible production system. When a new model must be integrated at a low volume due to an unpredictable market or a test series, but with the possibility for ramping up, it can be produced in an MFG like this. Enabling an MFG station to only process all geometry steps and no respot operations of a new model. Leading to a reduced cycle time in an MFG station and thus a higher capacity.

A.4 MFG station for new-model specific GEO-steps
When a new model, for example an EV, has comparable geometry as the ICEV predecessor, they can be produced in the same production system but with an additional MFG station. The principle is that a number of GEO-steps that are for the EV are done in existing, flexible, GEO stations. Furthermore, as seen in Figure 48, the stations are
connected to an MFG station that can perform the type specific operations for EV. This is the most efficient case of an MFG station for integration and for the production of new models in a Greenfield area. However, Case A.4 in a Brownfield scenario has the same logistical and joining-sequential problems as an MFG station for all the GEO-steps, Case A.3.

Figure 48 – Case A4: MFG station for new model specific GEO-steps.

6.1.2 Case B – Fluctuations in a Current Model

Models that are already in production have volume fluctuations due to the market and the demand. The fluctuation case is strongly related to product mix flexibility and capacity flexibility in a station, described in Chapter 2.1.2. An MFG station can prove itself useful as modular and scalable for a production with fluctuating volume changes. In Case B, an MFG station is put into following two, similar situations, which might have the same solution:

B.1 Increased volume of a low runner – Scalable MFG station

A new model, for example an EV, or a current low runner, can in future be produced in an MFG station at a low volume. If the demand of the EV is rising, the capacity in an MFG station is not enough and it forces an expansion by additional MFG stations. Figure 49 describes an example of three expansion steps of the scalable MFG station. During the initial production phase of a new model, an MFG station can provide GEO-step 1-4 within one station, and have an output of 25% EV. Second phase is when the volume increases, an MFG station can be divided into two stations. One station processes GEO-step 1+3 and the other GEO-step 2+4. The output of the EV is twice as high, by one additional station. In the third phase, the two MFG stations can be divided into four stations, and therefore meet a volume 100% EV. Consequently, an MFG station has been transformed into a high-volume production system.
B.2 Decreased volume of a high-runner

If the volume of a current high-running vehicle decreases during phase-out or a dip in demand. The model is then no longer profitable to produce in a high-volume production system and can instead be produced in an MFG station. Similar to the argument in previous paragraph, this situation will have to be contemplated to determine the most profitable solution for switching from a high-volume production system into an MFG station concept.

6.1.3 Case C – Breakdown in a Production System

Case C deals with a solution for using an MFG as a substitute when a breakdown occurs in a geometry station of a modular production system, as CubeTEC. The two subjects discussed in this case are modular fixtures and interchangeable handling- and joining equipment. The two subcases in Case C are divided into:

C.1 Modular system of inflexible tools

When inflexible fixtures, joining and handling equipment are used, it is important to have a modular strategy for quick and feasible changes of tools between the stations. If the required changeover time for setting up tools in an MFG station is shorter than the breakdown time in a GEO station of a production system, it will be feasible to use an MFG as a substitute during breakdown. Therefore, a modularized interface is necessary when inflexible tools are used in a production system.
C.2 Flexible tools in an MFG station

If highly flexible, but fixed tools are used in an MFG station, it can be possible for an MFG station to act as a substitute for the broken GEO station. Given that the MFG station has the flexibility to alternate the production between numbers of derivatives.

6.2 Analysis of New-Model Integration Cases

This part of the chapter holds an analysis of a new-model integration in an MFG station. The new-model integration case was described as one of several cases in Chapter 6.1- Case Generation. In the frame of this research, it was chosen to only perform an analysis on the case of a new-model integration from Chapter 6.1 as it is towards the objectives in this research.

To determine the most favorable solution, it is essential to compare the cases with respect to various factors. The factors relevant to compare before the choice of an integration case are: capacity in terms of volume output, the simplicity to integrate a new model in the system, required footprint of the production system or MFG station, flexibility between derivatives in the system and the required effort in terms of hardware installation. A comparison between the new-model integration cases is shown in Table 2 and followed by descriptions.

<table>
<thead>
<tr>
<th>Case A – New Vehicle Model</th>
<th>Capacity (Volume Output)</th>
<th>Simplicity in New-Model Integration</th>
<th>Footprint Utilization</th>
<th>Derivative Flexibility</th>
<th>Effort (Investment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 New Production System</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>A2 Independent MFG Station</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A3 MFG Station for all GEO-steps</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>A4 MFG Station for model specific GEO-steps</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>
6.2.1 Case A.1 – New production system

Building of a new production system for the successor secures the model for being built in high volumes due to a high number of relatively simple geometry station for each required GEO-step. Current production systems hold a certain flexibility within derivatives of a model but cannot alternate the production between all the derivatives or between models. The integration is less complex since the know-how already exists within the company and relatively standard equipment are used in the system. Due to a higher capacity, the footprint of a new production system is generally larger than an MFG station. Nevertheless, a complete production system always requires high effort in hardware installation and may not be suitable for a new model that is produced in low volumes.

6.2.2 Case A.2 – Independent MFG station

In Case A.2, resbot operations are integrated within the MFG station. That enables an MFG station to produce a new model independently and to not be bound to any current production system. Nevertheless, a completely independent integrated MFG station does not bring any further flexibility in a current production system since the two systems are working separately. The independent MFG station will induce an increased cycle time due to an impracticability to parallelize the GEO and RS operations, and as a result lower the capacity.

The advantages of an independent MFG station are found in the simple integration of new-models, together with high derivative flexibility and low footprint. An independent MFG station will not induce problems to a current production system since it uses isolated hardware and software. By adding or adjusting the hardware in the station, it can be able to produce complete assemblies of several derivatives in a model series. Since geometry- and resbot operations are common performed in one station, the utilization of factory footprint is considered to be at a high level.

6.2.3 Case A.3 – MFG station for all GEO-steps

Case A.3 applies when an MFG station is not integrated as an independent station nor in the existing GEO stations of a production system. An MFG station in Case A.3 handles all GEO-steps within one station, but utilizes the resbot operations from a production system.
Case A.3 is possible to apply in a Greenfield area of a CubeTEC scenario. But only partly possible in a CubeTEC Light or Light+ production. To have an MFG station integrated in a CubeTEC Light or Light+, the production system will have to be built in a logistic way for easy loading of parts into respot station from an external MFG station. Furthermore, a CubeTEC Light or Light+ production has the respot stations in a subsequent order after respective GEO station, and must therefore match the required joining methods and joining sequence required from an external MFG station. The cycle time in the MFG station is strongly related to the tool changes for the different GEO-steps in the station and will therefore induce a low capacity. Despite a low capacity, the integration Case A.3 includes a high derivative flexibility since the hardware for producing different variances and GEO-steps is kept within the station.

The required footprint of an MFG station in Case A.3 is minor to a new production system since all the GEO-steps are kept in one station. Nevertheless, an MFG station still utilizes the respot operations from another production system and brings a higher total footprint. On the other hand, combining a production system with an MFG station always reduces the hardware investments and parallelizes the operations for an increased capacity.

6.2.4 Case A.4 – MFG station for specific GEO-steps

In Case A.4, an MFG station only produces type-specific GEO-steps and is strongly bound to both geometry- and respot operations in a high-volume production system. An MFG station for the type-specific GEO-steps utilizes the interactive production system during a second lifecycle and will therefore decrease the total required investments.

The capacity of an MFG station in Case A.4 is higher than integration Case A.2 and A.3, since fewer number of GEO-steps are performed in an MFG station. Additionally, less numbers of GEO-steps reduces the required footprint for storing tools and other equipment around the station. To extend the number of GEO-steps, for the production of another derivative or a new model in Case A.4, will require new tools that must be integrated in the current station. Therefore, the derivative flexibility and the complexity of integrating a new model is considered to be relatively high.
7 Existing Concept and New Technologies

Within the project SBS, a concept for a modular geometry station has been generated. In this chapter, the function of the SBS concept is revealed together with an analysis of the pros and cons of the concept. Furthermore, after the SBS concept is presented, a chapter about technologies that can enable a higher grade of a system changeability follows.

7.1 SBS Modular Manufacturing Station

The SBS modular manufacturing station is a concept of an MFG station, generated by the SBS partner FFT. The concept is a one-level layout (see Figure 50) with robots that have a common interface for utilization of handling equipment and joining tools. Fixtures are modular for easy and fast changes.

The station itself involves a set-up of (Schneegans, 2018):

- 8 Industrial robots with 8 Universal docking systems
- 2 Mobile trolleys for part transportations
- 16 Trolleys for tool storage.

**Step 1: Unloading trolley – changing modular fixture**

An AGV drives into position A (Figure 50) in the station with the mobile trolley that contains a complete car-set of single parts. Handling robot 10RB_600 unloads parts required for the GEO-step from the trolley. 10RB_200 places the modular fixture in the center of the station. Finally, 10RB_600 load the parts into the modular fixture (Position 1).

**Step 2: Fixture of single parts**

The robots 10RB_400/800 dock onto the dedicated GEO-grippers (Figure 50; Position 2) and clutches them to the modular fixture to secure the parts in joining position.

**Step 3: Joining of single parts to one assembly**

The robots in step 3 performs parallel joining of the parts in teams of two:

Only joining robots: 10RB_300 together with 10RB_100.
GEO-gripping and joining robots: 10RB_400 together with 10RB_800.
Only joining robots: 10RB_500 together with 10RB_700.
**Step 4: Release of fixtures and loading of assembly**

After the required joining, the robots 10RB_400/800 dock onto the dedicated GEO-grippers that are attached to the modular fixture and releases the assembly. After that, the robot 10RB_600 picks the assembly from the modular fixture and loads it on the trolley in Figure 50; Position B.

![Diagram of SBS modular manufacturing station](image)

**Figure 50 – SBS modular manufacturing station (Schneegans, 2018).**

### 7.1.1 Analysis of the SBS Manufacturing Station

In the SBS station concept, robots are utilized to perform more than one type of operation. The principle is to have a modular and common interface between all the robots and the tools. Thus, enabling exchanges between different joining tools and handling tools.

Joining equipment is considered to have a low grade of flexibility due to relatively limited range of metal thickness and rigid geometries of the tools. However, the interface between numbers of joining equipment is developed as common. Therefore, equipment can be changed within one robot. The boundaries to have unlimited change of joining equipment are affected by factors such as: weld power, cooling water, air, signal requirements and construction of docking system. Interchangeable tools are stored around the station, reachable for docking to a robot.

GEO-steps 2, 3 and 4 for a specific model studied, shows that the stepwise construction tasks have similar interference geometries. It is therefore preferable to utilize a completely flexible tool
that does not require to be changed between the GEO-steps. Handling of assemblies and single parts in the SBS station are done with a total number of two handling grippers. The first is one dedicated gripper for handling single parts in the first GEO-step. The left CAD model in Figure 51 shows the gripper and that it can handle parts for the rear floor of four specific derivatives in one GEO-step.

The second gripper handles the assembly formed after the first GEO-step, as well as single parts for remaining GEO-steps. To the right in Figure 51, the gripper developed to handle the assembly on one side and single parts for several GEO-steps of a derivative, is shown. This gripper has a common interface for easy exchangeability, which means it is interchangeable and holds a certain level of internal flexibility. Nevertheless, it can handle all the GEO-steps of a model-derivative, it is limited to only this specific model-derivative.

![Figure 51 – Flexible gripper for single parts (left) and assemblies (right) (Schneegans, 2018).](image)

The two handling grippers in the SBS station can together handle all required GEO-steps of one derivative. Nevertheless, it requires tool changes. While the handling-tool changes in the SBS station can be considered as a bottleneck, the tool itself must be more flexible for several derivatives. Tools that are flexible within itself will reduce the number of changes and consequently induce a lower cycle time. If one tool can adapt for all derivatives in a model series, it will have full flexibility within the model’s flexibility corridor in Figure 52. However, if also a modular system for exchange is implemented for the flexible grippers, the whole station will have a high versatility to alternate the production between different model series.
Figure 52 – Flexibility and Versatility in the SBS station; models from: (Schneegans, 2018).

For fixing the single parts during each GEO-step, a pair of two model-dedicated GEO-grippers are used for each operation. The GEO-grippers are attached to a modular fixture by robots and are fixing the single parts during joining. Each part, for every GEO-step, requires a dedicated GEO-gripper, and the station will therefore hold a high number of GEO-grippers. The dedicated GEO-grippers are stored next to the robot, illustrated in Figure 53 (box 3).

In the center of the station in Figure 53 (box 4), a modular fixture is located and act as a basis for formation of a geometrical assembly. The GEO-grippers are attached to the modular fixture after all the parts, required for one GEO-step, have been positioned. In the SBS station concept, two modular fixtures are used for the completion of an assembly. GEO-step 1 is done in one modular fixture and cannot be performed in the same modular fixture as GEO-step 2-4 and vice versa. Therefore, it is a need for interchangeability between the two modular fixtures.

Material handling flexibility in the SBS-station concept is high. The material transports within the facility are exclusively performed by AGVs. The AGVs are driverless and can drive an unlimited number of paths in a non-sequenced order between various SBS stations or production systems.
7.2 Technologies that Define Changeability

In Chapter 2.6, several technologies that are currently used in a BiW production was outlined. In this chapter, current technologies are compared to new ones on the basis of modernizing. How changeability in hardware in a manufacturing station can go from dedicated to flexible and versatile equipment. A manufacturing station in this research refers to a geometry process in a BiW production. The described features relevant for a changeability alteration in a geometry station are listed under two main subjects: process enablers and logistic enablers. Single changeability enablers are together summarized in a matrix table for comparison and analysis in Chapter 8.1.

7.2.1 Process Enablers

Process enablers are mainly tools for handling and changing part properties. Commonly for tooling in a geometry station is to determine the level of changeability for each tool. The tools can roughly be divided into three approaches when designing and engineering tools:

- **Rigid & type-specific** tools that can handle and perform one activity.
- **Universal & flexible** tools that can adapt and adjust itself for several activities.
- **Interchangeable** tools with a common and modularized interface that enables a complete reconfiguration for other activities.

In this context, following topics will be discussed: flexible handling tools, adaptable and modular fixture tools, coupling elements and adaptable joining tools.
Flexible Handling Tools

Handling tools utilized by robots in an MFG station are grippers. Commonly for all types of grippers is the desire for a lightweight construction. A reduced weight of the gripper can either enable lifting of heavier parts or reduce the robot class required, and therefore cut the investment costs in a production station. Weight can be reduced in grippers by material or technical changes. A steel frame can be replaced by one in aluminum or CFRP, and a clamping device can be exchanged to another technology.

Rigid and type-specific grippers are engineered for producing high volumes of the same, or very similar model-geometries. The grippers are less expensive than the flexible ones due to a reduced complexity.

A universal and flexible gripper requires a higher investment and is profitable for the production of high volumes of varying geometries. A flexible gripper can handle a large variance of geometries without the need for exchange. The advantage of a flexible gripper is when different geometries are produced in sequence and there is no room for changing the gripper within the takt time. One example of a technology that can be used for an increased flexibility in a gripper is a suction device for sheet handling developed by Schmalz. Suction Cup Balance (SSCB) in Figure 54 can adapt each positioning rod, surrounding the suction cup, for various geometries and so enable a high tooling flexibility (Schmalz, 2016).

A system of interchangeable grippers can be implemented with either rigid or flexible grippers. Generally, for the usage of interchangeable grippers in an MFG station, the requirements are to have a: standardized and modular interface for exchange between the same or different robots and a changing time parallelized with other operations.
Adaptable and Modular Fixture Tools

The system of the adaptable NC Locators in a fixture tool is a way for increased flexibility. It allows to take body parts of different sizes and types and to precisely and quickly position them in a fixture. Depending on the shape of the body parts, the required mounting points of the positioning system are flexibly aligned in all three axes via the control system. This adjustment takes place within a few seconds. The slim system also shows a particularly easy installation and works with high positioning accuracy (Leantechnik, 2017).

The maximum versatility is given by modular fixtures. By modular elements with uniform mechanical interfaces, they are applicable to a large variety of parts. Due to the fast reactivity to changes, modular devices for production offer great advantages. The design of a modular fixture system ensures high accuracy and short deployment times through exchangeable fixtures. Because of the versatility, a modular device system can be used for different derivatives or models (Trummer, 1994). Lighter fixtures can be changed by a robot, while larger ones can be mounted on a rail in the floor for driving in and out of the work area inside the station.

However, rigid and flexible fixtures can also be designed for mounting on a rotary device. Each side of the rotating device features a type-dedicated fixture. The drawback with a rotary device is the limitation to only store a specific number of fixtures (Omar, 2011).

One option for a high versatility is a sub-modular fixture. The sub-modular fixture, shown in Figure 55, uses a baseplate where several sub-modules can be attached to (Keyvani, 2008). It can be configured for derivatives in a current model series, for other model series and also hedging for new, not yet implemented models. The fundamental strategy for a sustainable system of sub-modular fixtures is to have the sub-module changes highly automated in a process and to utilize a minimum number of two fixtures for having one of them rebuild during a stations process time.

Figure 55 – Principal figure of a modular fixture for machining operations (Keyvani, 2008).
**Coupling Elements**

A technology enabler for sub-modular systems of grippers and fixtures is coupling elements. A coupling must be able to transform forces and, in some applications, also signals and air. The Speedy couplings from (Roemheld GmbH, 2018) are developed for high lifting forces and can also be configured with multimedia connectors for necessary media transport (see Figure 56). With very high tolerances and a clamping and release time lower than 0.1 sec, it can enable quick and easy changes of modules.

![Image](https://via.placeholder.com/150)

*Figure 56 – Multimedia coupling on gripper for robot (Roemheld GmbH, 2018).*

**Adaptable Joining Tools**

The most flexible joining tool for a high number of material combination is the Self-Piercing Riveting. However, the high flexibility demands a lot of cycle time since the tool must be configured for each material combination. The different combinations of material demands several types of dies and rivets. The flexibility to change rivet type and die profile in a manual process is limited and time consuming. However, the SPR-tool manufacturer Böllhoff has developed an automated solution for external changes of, up to eight, die profiles during a changing time under five seconds (see Figure 57). Together with a magazine feed that can process up to four (optional eight) different types of rivets, the flexibility within the SPR tool will increase dramatically (Böllhoff GmbH, 2018). The only limiting factor for full versatility in the tool, is the C-shaped geometry of the tool.
Regarding the flexibility in tools for resistance spot welding is there not any new solutions. To increase the flexibility of RSW tools in a manufacturing station, the universal solution today is to use a C-shaped gun constructed for aluminum. Aluminum spot welding require higher currents and lower forces. Due to the high currents, it would not be possible to weld aluminum with a gun constructed for steel. But the reverse alternative is possible, and therefore is the aluminum gun more flexible in terms of material combinations.

C-shaped guns have a higher flexibility because the electrode movement is collinear and can therefore adapt for more combinations than an X-shaped one. However, an X-shaped gun has a higher accessibility due to a slimmer construction.

### 7.2.2 Logistic Enablers

Logistic enablers are technologies related to the material- and tool logistic in a production system. This chapter focuses on cooperating robots and AGVs. Primary on AGVs since it is a relatively new technique used in BiW production.

**Cooperating Robots**

Cooperating robots are used to reduce the numbers of fixtures in a station. Two robots that communicates with each other can fixture and move the parts for enabling greater range of accessibility for the joining robots and consequently reduce the cycle time (Michalos, et al., 2015). Cooperating robots work after the master-slave principle. In principle, one robot (master) specifies the movement. The task of the slave robot is to follow these movements and position synchronously. Another feature of this application is the load sharing. It means that the load is gripped by both robots and moved within the range of reach.
Automated Guided Vehicle (AGV)

A new concept of material supply and material transports in a BiW production is by AGVs. An Automated Guided Vehicle (AGV) is a driverless, self-driving vehicle for transportation of material and goods. An AGV can use various techniques for transporting the goods. First, there are AGVs for transporting pallets, similar to forklifts. Secondly, AGVs with an inbuilt lifting system for moving objects such as shelves, trolleys or special constructions. Thirdly, ones with a controlled pin for clenching on to a trolley or similar for towing.

An AGV drives from point A to B according to a pre-programmed route or a given order from a parent system. The routing flexibility can differ between AGVs. There are mainly two parameters that determine the routing flexibility: the navigation system and the type of steering. Navigation by inductive guidance or by magnet tape/spots is inflexible in routing options since the AGV follows a pre-defined route. Laser triangulation, optical scanners and SLAM navigation enables the AGV to drive from point A to B in an optimized route. The fixed obstacles are scanned by the vehicle and stored internally. The steering types varies depending on how many wheels and the degree of freedom each wheel has. KUKA has developed their own AGVs (KMP 1500) with wheels that can drive omnidirectional (see Figure 58). The KMP 1500 has a lifting system and a capacity of 1500 kg together with an accuracy of +/- 5 mm (KUKA AG, 2018).

Figure 58 – KUKA KMP 1500 (left); Omnidirectional wheel (right) (KUKA AG, 2018).
8 Conceptualization of MFG Stations

This chapter includes the formation of a morphological chart compiling the technologies that were described in 7.1.1 and reveals how a combination of technologies can enable a higher level of changeability in a manufacturing station. Furthermore, several concepts of an MFG station is generated through a deeper morphological laboratory of how different hardware technologies can be combined in a number of alternatives for the formation of several concepts. The concepts are then analyzed and compared with respect to changeability, capacity and footprint.

8.1 Morphological Analysis

In a systematic and analytical way a morphological chart is used to generate principal solutions with available resources (Smith, 2007). Figure 59 describes the stepwise construction of a morphological chart. The first step in the chart generation is to identify features that must be performed in a station. Secondly, available resources that are possible solutions to the feature are filled in. Finally, the concept creation takes place and a number of possible solutions can be outlined.

8.1.1 Compilation of a Morphological Chart

In Table 3, a morphological chart of the resources in a manufacturing station, the principles and related functional design features, is described. Features 1-5 are directly related to process changeability, while features 6-11 are related to logistical changeability. The columns from left to right represent an increasing level of changeability for each feature.
Table 3 – Morphological Chart of technologies in a producing station.

<table>
<thead>
<tr>
<th>Changeability</th>
<th>Dedicated</th>
<th>Flexible</th>
<th>Versatile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature</td>
<td>(1) Very Low</td>
<td>(2) Low</td>
<td>(3) Medium</td>
</tr>
<tr>
<td>Handling Grippers</td>
<td>Rigid Clamps</td>
<td>Rotating Two-sided</td>
<td>Pneumatic</td>
</tr>
<tr>
<td>Fixture Tools</td>
<td>Rigid Fixture</td>
<td>Rotating Two-sided</td>
<td>NC-LOCATORS</td>
</tr>
<tr>
<td>GEO-Grippers</td>
<td>Combined with fixture</td>
<td>Rigid clamps (Feed to RB)</td>
<td>NC-LOCATOR (Feed to RB)</td>
</tr>
<tr>
<td>Self-Piercing Riveting</td>
<td>Rigid C-Shape</td>
<td>Reversed side of drive</td>
<td>Internal Die-changer</td>
</tr>
<tr>
<td>Resistance Spot Welding</td>
<td>Stationary gun</td>
<td>Gun geometry from Special portfolio</td>
<td>X- &amp; C-Shape gun Steel Standard portfolio</td>
</tr>
<tr>
<td>Robot Mounting &amp; Working Range</td>
<td>Standing 1st level</td>
<td>Standing 2nd level</td>
<td>Hanging</td>
</tr>
<tr>
<td>Single-Part Storage</td>
<td>Fixed</td>
<td>Rotating Manual drum</td>
<td>Foldable toggle clamps</td>
</tr>
<tr>
<td>Tool Logistic</td>
<td>Fixed</td>
<td>Rotating table 1-level</td>
<td>Rotating table 2-level</td>
</tr>
<tr>
<td>Material Logistic</td>
<td>LCA</td>
<td>Chain Conveyor</td>
<td>EMS</td>
</tr>
<tr>
<td>AGV Navigation</td>
<td>Inductive Guidance</td>
<td>Magnetic Tape</td>
<td>Magnetic Spots</td>
</tr>
<tr>
<td>AGV Steering</td>
<td>No steering</td>
<td>Diff Drive</td>
<td>Three-Wheel</td>
</tr>
</tbody>
</table>

1 Indirect effect on station flexibility. 2 When material or tool logistic is executed by an AGV.
8.1.2 Coherence between Parameter Fields

The interchangeability of tools is a central parameter for driving other parameters during a morphological analysis. Even though a complete tool is interchangeable, and the system has a high changeability, the tool itself can have a certain grade of changeability. Therefore, the interchangeable tools must be configured together with another field from the same row in the table to create coherence. This means that interchangeable tools hold the highest level of changeability but that the tools itself can be deemed to have different levels of changeability.

The same principle is applied in the logistical field. If the single-part storages are transported on an interchangeable platform, the platform itself must have a certain grade of changeability. If the transports of tools are by a robot mounted on an AGV, it must be configured with another field on the same row since the tools can also be stored in the station in different ways. Material transports that are executed by AGVs requires a configuration in the feature fields: AGV navigation and AGV steering.

Table 4 shows the feature that are marked as driving parameters in a principle of a morphological chart. Table 5 shows the principle in a graphical version of the same chart.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Coherence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td></td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td></td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td></td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td></td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td></td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td></td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Coherence in a morphological chart.
Table 5 – Coherence in a morphological chart (graphical).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Dedicated</th>
<th>Flexible</th>
<th>Versatile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) Very Low</td>
<td>(2) Low</td>
<td>(3) Medium</td>
</tr>
<tr>
<td>Handling Grippers</td>
<td>Rigid Clamps</td>
<td>Rotating Two-sided</td>
<td>Pneumatic</td>
</tr>
<tr>
<td>Fixture Tools</td>
<td>Rigid Fixture</td>
<td>Rotating Two-sided</td>
<td>NC-Locators</td>
</tr>
<tr>
<td>GEO-Grippers</td>
<td>Combined with fixture</td>
<td>Rigid clamps (fixed to RB)</td>
<td>NC-Locator (fixed to RB)</td>
</tr>
<tr>
<td>Self-Piercing Riveting</td>
<td>Rigid C-Shape</td>
<td>Reversed side of drive</td>
<td>Internal Tie-changer Multi-Magazines</td>
</tr>
<tr>
<td>Resistance Spot Welding</td>
<td>Stationary gun</td>
<td>Gun geometry from Special portfolio</td>
<td>X- &amp; C-Shape gun Steel Standard portfolio</td>
</tr>
<tr>
<td>Robot Mounting &amp; Working Range(^1)</td>
<td>Standing 1(^{st}) level</td>
<td>Standing 2(^{nd}) level</td>
<td>Hanging</td>
</tr>
<tr>
<td>Tool Logistic</td>
<td>Fixed</td>
<td>Rotating table 1-level</td>
<td>Rotating table 2-level</td>
</tr>
<tr>
<td>Material Logistic</td>
<td>LCA</td>
<td>Chain Conveyor</td>
<td>AGV</td>
</tr>
<tr>
<td>AGV Navigation(^2)</td>
<td>Inductive Guidance</td>
<td>Magnetic Tape</td>
<td>Magnetic Spots</td>
</tr>
<tr>
<td>AGV Steering(^2)</td>
<td>No steering</td>
<td>Diff Drive</td>
<td>Three-Wheel</td>
</tr>
</tbody>
</table>

\(^1\) Indirect effect on station flexibility. \(^2\) When material or tool logistic is executed by an AGV.
8.1.3 Changeability Measurements

A changeability measure describes the level of changeability a producing station can achieve with the available hardware in terms of process features and logistic features that is utilized. The total changeability measure emerges from several sub-indexes. A sub-index is the changeability level for one specific feature.

When determining a sub-index of feature, the single technologies must be considered in a system. For example, a tool that is adjustable to handle a number of geometries for several derivatives is considered to have a medium level of changeability. Then there are tools which only can handle one or two geometries that have a low changeability. When a low-changeability tool is designed with a modular interface for quick exchange in a station, then the system changeability is increased, and the rigid tool is, compared to the adjustable tool, even more flexible in a system.

In order to compute and measure the total changeability level in a system, each column in the morphological chart is given a certain changeability rate that is used in further comparisons.

Each field of feature in the morphological chart cannot be mixed. First the total changeability of each row must be calculated. Each row can be situated in a matrix as Eq. (8-1).

\[
R_{10} = \begin{bmatrix} a_{11} & a_{12} & a_n \end{bmatrix} \\
R_{20} = \begin{bmatrix} a_{21} & a_{22} & a_n \end{bmatrix} \\
R_n = \begin{bmatrix} a_n & a_n & a_n \end{bmatrix}
\] (8-1)

Next step is to determine where improvements can be implemented, sub-values of changeability for each row in the table has to be determined to compare features on an equal basis. Each sub-group average changeability is obtained by using Eq. (8-2).

\[
AVG_R = \frac{1}{n} \sum_{i=1}^{n} a_i = \frac{1}{n} (a_{11} + a_{12} + \cdots + a_n)
\] (8-2)

Whereas the average of each feature in a row Eq. (8-3) can be summarized vertically by the usage of Eq. (8-4).
The average result represents a station's changeability with respect to the technologies used. To transform the calculated changeability value into text, it can be converted to the definitions listed in Table 7.

**Table 6 – Changeability measurements.**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Changeability</th>
<th>Total/Feature</th>
<th>Avg./Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td>Very Low</td>
<td>1</td>
<td>EQ 8-1</td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td>Low</td>
<td>2</td>
<td>EQ 8-2</td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td>Medium</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td>Extended</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td>High</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td>Very High</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 7 – Station Changeability elucidations.**

<table>
<thead>
<tr>
<th>Score</th>
<th>Changeability</th>
<th>Highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Low</td>
<td>A station that is dedicated to produce one derivative in a model series in a current portfolio.</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>A station that is dedicated to produce more than one derivatives in a model series in a current portfolio.</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>A station that is flexible and can adapt for an alternated production between derivatives of one model in a current portfolio.</td>
</tr>
<tr>
<td>4</td>
<td>Extended</td>
<td>A station that is flexible and can adapt for an alternated production between numbers of models in a current portfolio.</td>
</tr>
<tr>
<td>5</td>
<td>High</td>
<td>A station that is versatile for coming models in an unknown portfolio by universal hardware</td>
</tr>
<tr>
<td>6</td>
<td>Very High</td>
<td>A station that is versatile for coming models in an unknown portfolio by an optimized hardware interchangeability.</td>
</tr>
</tbody>
</table>
8.2 Concept Laboratory of an MFG Station

In this section, a number of concepts are generated and configured with different hardware based on the morphological table. The total station changeability for comparison is calculated according to formulas in Chapter 8.1.3. An MFG station can utilize different variants of tools and equipment from a common portfolio and as a result take different forms. It is therefore important to choose equipment along what is desirable in terms of changeability, capacity and footprint.

The first concept laboratory is a determination of the total changeability in the current modular SBS station. The outcome is used to compare the current concept with the new ones on equal basis. Succeeding concepts are developed versions of the current SBS concept, each one is assembled with a desire for maximization in one of respective areas: changeability, capacity and footprint.

A few changeability enablers do not exist in hardware today or are not yet suitable for BiW production. Therefore, those are not selected when optimal concepts are generated. Following MFG station concepts have been assembled with a combination of various hardware: High Changeability A & B, High Capacity A & B and Low Footprint. In the overviewsing layouts, abbreviations are used according to Figure 60. Industrial robots for handling of only single parts and assemblies are considered to be in the interval of 250-300 kg sizes. Joining robots are also in 250-300 kg sizes, while multi-purpose robots are slightly larger, in the range of 300-400 kg. Handling robots that handles a modular fixture are in the size of 500-600 kg.

\[\text{Handling Robot} \quad \text{Joining Robot} (\text{RSW, SPR}) \quad \text{Multi-Purpose Robot} (\text{RSW, SPR, Handling}) \]

Figure 60 – Abbreviations used in concept layouts.

8.2.1 Concept SBS Manufacturing Station

The concept SBS manufacturing station is described in Chapter 7.1. Table 8 shows the morphological analysis and the changeability measurement for the SBS modular manufacturing station. The station complies process technologies with a high interchangeability of tools. The driving factors for the changeability in the SBS station is that the station utilizes interchangeability
between rather model-specific tools but in a modular way. Consequently, this requires a high number of tools to be stored next to each robot. The tool logistic, as well as material logistic is performed by AGVs which has a high level of logistical changeability.

Table 8 – Morphological analysis of a Modular SBS Manufacturing Station.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Changeability</th>
<th>Very Low</th>
<th>Low</th>
<th>Medium</th>
<th>Extended</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.2.2 Concept High Changeability A

Table 9 shows the morphological solution and the changeability measurement for the first station with high changeability. The concept A with a high changeability utilizes interchangeable- and submodular tools. The result is a maximized changeability within one station. A high process changeability is enabled through a complete in-station system for the rebuilding of handling- and fixture tools. Handling robots alternates between two modular tools for the parallelization of process time and tool-rebuilding time. When the tool has been placed in the free position at the rebuilding area, a robot or a human can do the modular rebuilding required for the succeeding GEO-step.

The station utilizes RSW tools that are flexible for aluminum and steel welding of various geometries, but also exchangeable if other geometries must be welded. The SPR tool changes the dies in an external device that can store several different types of dies. An external die changer will not affect the geometry of the gun and therefore not interfere with the accessibility. Together with a multi-feeding system of rivets, the SPR tools gets a high flexibility with the only drawback of a rigid C-shaped gun.
The logistic in the concept has also a high changeability. The material transports are executed by AGVs with the highest changeability in navigation and steering. Parts are stored on the AGVs by a sub-modular platform with interchangeable bayonet-modules that can be changed depending on the geometry of the parts. Since the tooling in the station are mainly in sub-modules, only the required sub-modules are transported into the station by small-size AGVs. Since the station holds a high changeability by having areas for sub-modular changes, the footprint is dramatically increased. Figure 61 shows an overviewing layout with description of the station. Figure 62 shows the station layout in perspective.

Figure 61 – Concept High Changeability A overview.

Figure 62 – Concept High Changeability A perspective.
8.2.3 Concept High Changeability B

Table 10 shows the morphological solution and the changeability measurement for the second station with high changeability. The concept B with a high changeability utilizes interchangeable tools with a high grade of adaptability. The number of type-specific tools are, compared to the SBS concept, reduced in the station. The SPR tools are equipped with an internal die-changer for the possibility to adapt the tool between a fixed numbers of dies.

The logistic in the station is at a high level of changeability. Parts are transported on adaptable platforms that holds a number of configurations. The platforms are transported by highly flexible AGVs. Additionally, the flexible and adaptable tools are stored in a fixed position in the station. The adaptable fixtures and special tools are transported by an AGV into the station when another vehicle is produced.

Figure 63 shows an overviewing layout with description of the station. Figure 64 shows the station layout in perspective. The concept B with a high changeability consumes just slightly more footprint than the SBS station.
Figure 63 – Concept High Changeability B overview.

1. Riveting tools with internal die changers for high flexibility and lower amount of required tools.
2. GEO-grippers with NC-locators for adapting to several geometries.
3. Modular fixture with NC-locators for adapting to several geometries.
4. AGV perform quick and easy exchange of modular fixture.

Figure 64 – Concept High Changeability B perspective.
Table 10 – Morphological analysis of High Changeability Concept B.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Changeability</th>
<th>Very Low</th>
<th>Low</th>
<th>Medium</th>
<th>Extended</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.2.4 Concept High Capacity A

Table 11 shows the morphological solution and the changeability measurement for the first station with high capacity. The concept A for high capacity utilizes relatively dedicated tools. Joining tools have a certain grade of internal flexibility, but the concept is mainly toward an interchangeability of joining tools and a high versatility. Since a stations cycle time is mainly affected by tool changes of handling grippers and fixtures, the time for changing joining tools are parallelized and therefore not the bottleneck for a higher capacity. Handling tools are mounted on three robots whereof two are mounted on a 7-axis.

The exchange of fixtures is not by a robot nor an AGV. Changes are done through a linear axis that drives dedicated fixtures in an out of the station. The linear axis is expandable for additional fixtures for newly-integrated models or other derivatives. Additionally, the fixtures can be loaded with parts during a stations productive time. The result is a high utilization of the robots, as well as short cycle times. Neither does the station utilize GEO-grippers, since each fixture holds the required clamping devices for fixing the parts. A system with linear axis consumes more footprint than the SBS station due to the storage of four or more different fixtures in one station.

The logistic in the system are supported by low-flexible AGVs. Joining tools are stored on rotating tables in the station for a high utilization of tools between several robots. The joining
tools are exchanged from the table by a robot that is mounted on an AGV. The exchange system gives the opportunity to utilize one robot for several rotating tool tables.

Figure 65 shows an overviewing layout with description of the station. Figure 66 shows the station layout in perspective.

**Figure 65 – Concept High Capacity A overview.**

**Figure 66 – Concept High Capacity A perspective.**
8.2.5 Concept High Capacity B

Table 12 shows the morphological solution and the changeability measurement for the second station with high capacity. The concept B for high capacity is similar to the SBS station. The main differences in the process is that high capacity B uses internal die changers for the SPR tools and the fixture alternation between different GEO-steps are done by a turning table with two fixture positions. However, fixtures on the rotating table can also be changed by the large robot.

The logistic of tools in and out from the station is done by AGVs driving a trolley with the tool. Nevertheless, a number of tools are also stored fixed in the station since they hold a high internal flexibility. The concept for high capacity B consumes slightly more footprint than the SBS station.

Figure 67 shows an over-viewing layout with description of the station. Figure 68 shows the station layout in perspective.
Figure 67 – Concept High Capacity B overview.

1. Robot only handles loading/unloading of assemblies.
2. GEO-grippers that are type-specific are stored in an efficient way in the station.
3. Fixtures are placed on a rotating table that can alternate between two models or GEO-steps.
4. Large robot for handling single parts and exchange of modular fixture.

Figure 68 – Concept High Capacity B perspective.
Table 12 – Morphological analysis of High Capacity Concept B.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Changeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td>Very Low</td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td>Low</td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td>Medium</td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td>Extended</td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td>High</td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td>Very High</td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Logistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling Grippers</td>
<td>1</td>
</tr>
<tr>
<td>Fixture Tools</td>
<td>1</td>
</tr>
<tr>
<td>GEO-Grippers</td>
<td>1</td>
</tr>
<tr>
<td>Self-Piercing Riveting</td>
<td>1</td>
</tr>
<tr>
<td>Resistance Spot Welding</td>
<td>1</td>
</tr>
<tr>
<td>Robot Mounting &amp; Working Range</td>
<td>1</td>
</tr>
<tr>
<td>Single-Part Storage</td>
<td>1</td>
</tr>
<tr>
<td>Tool Logistic</td>
<td>1</td>
</tr>
<tr>
<td>Material Logistic</td>
<td>1</td>
</tr>
<tr>
<td>AGV Navigation</td>
<td>1</td>
</tr>
<tr>
<td>AGV Steering</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feature</th>
<th>Changeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td>Very Low</td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td>Low</td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td>Medium</td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td>Extended</td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td>High</td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td>Very High</td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
</tr>
</tbody>
</table>

| High Capacity B   | Avg. Process Changeability | 3.48 |
|                  | Avg. Logistic Changeability | 3.19 |
|                  | Avg. Total Station Changeability | 3.34 |

8.2.6 Concept Low Footprint

Table 13 shows the morphological solution and the changeability measurement for the station with low footprint. The concept of low footprint has a matching set-up of process- and logistic features as the SBS station. The main difference is the mounting of robots.

In a low-footprint concept, industrial robots are mounted on a second level to reduce footprint. The principle is to utilize a stations volume and thus reduce footprint. The second level are also used for storing handling gripper for several geometries.

The footprint is reduced by the usage of omnidirectional steered AGVs. An AGV that can drive in any direction does not consume as much floor space for turning radiuses. Since omnidirectional steering also can increase the possible routing alternatives for the AGV, the logistical changeability increases.

Figure 69 shows an overviewing layout with description of the station. Figure 70 shows the station layout in perspective.
Figure 69 – Concept Low Footprint overview.

1. AGVs with omnidirectional steering and a platform with sub-modular bayonet couplings.
2. Handling robots are mounted as standing on 2nd level and hanging for optimization of floor space.
3. Joining tools are mounted on trolleys that are transported in the station by AGVs.
4. Large robot for exchange of modular fixture and handling of GEO-grippers.

Figure 70 – Concept Low Footprint perspective.
8.3 Capacity Analysis – Station Cycle Time

Cycle time analyses have been performed for each concept to determine the capacity in terms of jobs per hour. The data in Table 14 represent the results from the complete analyses that can be found in Appendices. As general in the concepts of an MFG station, two robots perform joining simultaneously and parallel to each other. Therefore, they can be merged together during the cycle time analysis. The cycle time for each of the four GEO-steps is summarized to represent the total time for the completion of one assembly. The stations cycle time was transferred into jobs per hour for further comparisons of the concepts by using Eq. (8-5).

\[
\text{Jobs per Hour (Jph)} = \frac{3600}{\text{Cycle Time, } CT \text{ (seconds)}}
\]  

**Table 13 – Morphological analysis of Low Footprint Concept.**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Changeability</th>
<th>Very Low</th>
<th>Low</th>
<th>Medium</th>
<th>Extended</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Handling Grippers</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2 Fixture Tools</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3 GEO-Grippers</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4 Self-Piercing Riveting</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5 Resistance Spot Welding</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>6 Robot Mounting &amp; Working Range</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>7 Single-Part Storage</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>8 Tool Logistic</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>9 Material Logistic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>10 AGV Navigation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>11 AGV Steering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 14 – Cycle Time analysis of MFG Concepts.**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cycle Time CT (seconds)</th>
<th>Jobs per hour (Jph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS 1 station</td>
<td>478</td>
<td>7</td>
</tr>
<tr>
<td>High Changeability A (App. 1)</td>
<td>450</td>
<td>8</td>
</tr>
<tr>
<td>High Changeability B (App. 2)</td>
<td>372</td>
<td>10</td>
</tr>
<tr>
<td>High Capacity A (App. 3)</td>
<td>198</td>
<td>18</td>
</tr>
<tr>
<td>High Capacity B (App. 4)</td>
<td>429</td>
<td>8</td>
</tr>
<tr>
<td>Low Footprint (App. 5)</td>
<td>418</td>
<td>9</td>
</tr>
</tbody>
</table>
9 Results and Proposals of MFG Concepts

In this chapter, the results of the creative concepts are presented with respect to influencing factors. It is important not to see a creative concept as a finished product. They are relatively rough drafts that give the idea of how a solution could take shape.

9.1 Summary of Major Findings

The data in Table 15 are the results from the concept laboratory and the analysis of each concept.

Table 15 – Summary of Concept data.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Process Changeability</th>
<th>Logistic Changeability</th>
<th>Capacity Jobs per Hour (CT)</th>
<th>Footprint (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS Station</td>
<td>3,68</td>
<td>3,25</td>
<td>7 (478)</td>
<td>169</td>
</tr>
<tr>
<td>High Changeability A</td>
<td>5,03</td>
<td>5,08</td>
<td>8 (450)</td>
<td>304</td>
</tr>
<tr>
<td>High Changeability B</td>
<td>4,03</td>
<td>4,50</td>
<td>10 (372)</td>
<td>191</td>
</tr>
<tr>
<td>High Capacity A</td>
<td>2,78</td>
<td>3,50</td>
<td>18 (198)</td>
<td>235</td>
</tr>
<tr>
<td>High Capacity B</td>
<td>3,48</td>
<td>3,19</td>
<td>8 (429)</td>
<td>191</td>
</tr>
<tr>
<td>Low Footprint</td>
<td>3,92</td>
<td>4,58</td>
<td>9 (418)</td>
<td>132</td>
</tr>
</tbody>
</table>

9.2 Result in Radar Chart

All variables are converted into percentage in Table 16 for comparing the new concepts with the SBS station. Radar charts for each concept are then generated and presented in Figure 71.

Table 16 – Percentage comparison of MFG concepts.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Process Changeability</th>
<th>Logistic Changeability</th>
<th>Capacity</th>
<th>Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS Station</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>High Changeability A</td>
<td>137%</td>
<td>156%</td>
<td>114%</td>
<td>180%</td>
</tr>
<tr>
<td>High Changeability B</td>
<td>110%</td>
<td>138%</td>
<td>143%</td>
<td>113%</td>
</tr>
<tr>
<td>High Capacity A</td>
<td>76%</td>
<td>108%</td>
<td>257%</td>
<td>139%</td>
</tr>
<tr>
<td>High Capacity B</td>
<td>95%</td>
<td>98%</td>
<td>114%</td>
<td>113%</td>
</tr>
<tr>
<td>Low Footprint</td>
<td>107%</td>
<td>141%</td>
<td>129%</td>
<td>78%</td>
</tr>
</tbody>
</table>
Figure 71 – Radar Charts for MFG concepts.
Respective presented concept can be summarized as followed:

**SBS station:**
- Medium to extended changeability due to exchangeable but dedicated equipment.
- Low capacity due to high cycle times for exchanging handling grippers.
- Footprint is incident to the number of equipment that are stored in the station.

**High Changeability A:**
- High changeability because of a sub-modular system of equipment.
- Unchanged capacity due to equipment changes required for parallel rebuilding.
- Large footprint due to areas for rebuilding sub-modular equipment in station.

**High Changeability B:**
- Extended changeability due to adjustable and flexible equipment.
- High capacity because of less tool exchanges.
- Slightly more footprint than the SBS station because of additional 7-axis for robots.

**High Capacity A:**
- Medium to extended changeability because of an expandable system for fixture changes.
- High capacity due to several fixtures and a parallel loading of them.
- Large footprint because of a fixture exchange system and rotating tool tables.

**High Capacity B:**
- Medium to extended changeability due to exchangeable but dedicated equipment.
- Slightly higher capacity than the SBS station due to quick alternations between fixtures.
- Slightly more footprint than the SBS station because two-sided AGV parking slots.

**Low Footprint**
- Extended changeability due to adjustable and flexible equipment.
- Capacity as the SBS station due to high cycle times for exchange of handling grippers.
- Low footprint due to second-level mounted robots.
10 Integration of an MFG Station

This chapter contains discussions regarding the capacity alternation and the difficulties in technical aspects and logistic flow for the integration of an MFG station in a production scenario. The production scenarios studied in this research are earlier described as Brownfield and Greenfield in Chapter 4.

10.1 Scalable Capacity

A new model can be integrated in the production through an MFG station. An MFG station will however affect the production system it is integrated into. An MFG station that interacts with the respot operations from the production system will affect the current volumes of the ICEV. However, when an MFG is implemented as an independent station additional to a conventional line, it can produce, for example, the complete EV. The capacity can be scalable depending on if the MFG station is implemented as a single station, as two parallel stations, as one station with less GEO-steps or as one station that holds internal respot operations. Due to confidentiality, the diagrams do not contain actual numbers nor percentage of the distributed volumes.

10.1.1 One MFG station

The conventional approach is that the number of jobs per hour stays within the capacity of the production module. Figure 72 (left) shows an MFG station that holds all four GEO-steps and interacts with, in this case, CubeTEC, for the required respot joints. Figure 72 (right) displays how the volumes can be alternated between the ICEV and the BEV in an interacting system containing CubeTEC and an MFG station. The concepts generated in Chapter 8 enables a higher capacity of the BEV, but will consequently generate a bottleneck in the production system and reduce the capacity of the ICEV.

Figure 72 – Flowchart four GEO-steps (left) and Capacity diagram (right).
Figure 73 (left) shows the principal material flow when an MFG station is integrated for producing the model-specific GEO-steps for the EV. The diagram in Figure 73 (right) shows the capacity when the MFG station holds the required respot operations between the two GEO-steps. The cycle time for each MFG concept including the respot operations that were used for the calculation can be found in Appendix 6-10.

If the MFG station does not hold internal respot operations but utilize the respot operations from the production system, the volumes would be increased since the respot operations consumes cycle time. Figure 74 shows the flowchart and the capacity when an MFG station also utilizes the respot operations from the production system.
10.1.2 Two parallel MFG stations excl. Respot

Figure 75 (right) shows how the volumes in CubeTEC changes when the four GEO-steps in an MFG station is separated into two stations for parallelization (Figure 75 (left)). However, a further increase in the MFG stations capacity exceeding 50% of the total volume is not sensible, because then the capacity of 50% EV is exceeded and it makes more sense to exchange the work contents of the MFG station with those of the conventional geometry stations.

10.1.3 One MFG station incl. Respot

If the conventional way of planning the capacity within the volume of the production module is excluded from the calculation, volumes of a BEV can be added through an MFG station that holds all necessary respot operations. The capacity in the MFG station will be low, but the total volume in the production will be higher. Figure 76 (left) shows an MFG station that is producing the BEV completely distant from the production system. The capacity in the SBS station is low but can be increased via the concepts generated in Chapter 8.
10.2 Conventional System: Occluded Integration

A conventional production line for subassemblies performs as a sequential and rigid system without any other constrains to a sub-system. Geometry operations, as well as respot operations are performed one after each other and are strongly related. For the integration of an MFG station in the current flow of a conventional line, it will require an excessive amount of work to rebuild the hardware in the line and enable assemblies from an MFG station to access the processes. Additionally, the logistic of single parts and assemblies are exclusively moved internally by robots and externally by forklifts. An external handling of assemblies by forklifts between an MFG station and a conventional production line will not be profitable in a serial production due to unknown transport times in combination with workers bound to a takt time.

10.3 CubeTEC Light: Limited Integration

Each station in CubeTEC Light can be seen as a combined station because it holds both geometrical and respot joining. Transports between the combined stations are by a rigid conveyor system. However, transport of single parts from a supermarket to the first combined station is performed by an AGV system. This means that CubeTEC Light, unlike a conventional line, can interact with driverless vehicles. For the interaction between a production system and an MFG station, a vital part is to have a production system with an interface that enables AGV transports in and out of the station.

CubeTEC Light and an MFG station can utilize the same principle of a supermarket loading. When an AGV has been loaded, it can drive from the supermarket to either an MFG station or a combined station in the production system. When the geometrical joints of the assembly have been processed in an MFG station, the part will be transported to a combined station that holds the necessary respot operations. The obstruction follows by this example. If an MFG has been performing GEO-step 2 of an assembly, the assembly has to go to combined station 2 to perform the respot operation. To enter combined station 2, the platform which holds the assembly need to be detached from the AGV at combined station 1 and then go by combined station 1 via the conveyor system to reach the entrance of combined station 2. At combined station 2, it is only desirable to perform the respot joints on the assembly coming from an MFG station. Despite the fact that combined station 2 combine geometry operation and respot operation after each other, will lead to that the assembly from an MFG station have to be handled through the geometry operation to reach the desired respot equipment.
There are two problems for the interaction in terms of hardware:

1. At each combined station, there need to be an entrance in the conveyor system for the AGV to drive into and to detach the platform containing the assembly, which is illustrated as circle in Figure 77. This is mandatory to avoid transportations of assemblies from an MFG station through all the combined stations in a CubeTEC Light system.
2. Handling tools that are required in the respot station need to be flexible enough to handle geometries from an MFG station. If not, the need to be adjusted or changed.

Figure 77 – Interaction problem between an MFG station and CubeTEC Light.

Figure 78 describes the routing between CubeTEC Light and an MFG station. Summarized, an interaction between CubeTEC Light and an MFG station requires changes in hardware regarding the conveyor logistic and the interaction with the respot process in the combined stations.

A possible solution to produce assemblies in an MFG station in CubeTEC Light is to perform both geometrical operations together with respot operations within the station. The case is described in chapter 6.2.2. The MFG station will only perform type-specific GEO- and respot steps and the combined stations in CubeTEC Light will perform the GEO-steps that are commonly shared with the currently produced model.
The disadvantage is that the full capacity of the production system will be decreased since the combined stations cooperating with the MFG station become bottlenecks. For example, if a current production system produces 100% ICEV without interaction with an MFG station. With the interaction of an MFG station that can produce 25% EV, the production system is, simultaneously, only able to deliver 75% ICEV.

Figure 78 – Integration of an MFG station in CubeTEC Light.

**10.4 CubeTEC Light+: Partial Integration**

Combined stations are also utilized in CubeTEC Light+. The main difference to CubeTEC Light is the material flow between the combined stations. Instead of a fixed conveyor system, CubeTEC Light+ uses AGVs for the transports of assemblies. Therefore, the combined stations can be seen as completely separated from each other and there is a higher level of changeability in terms of sequencing.

Figure 79 describes the routing of AGVs from an MFG station to the non-sequenced area of combined stations in CubeTEC Light+. Furthermore, the AGV transports is an advantage for the integration of an MFG station. The disjointed combined stations of CubeTEC Light+ can enable the AGV to drive parts from an MFG station directly to the combined station that holds the required respot or GEO-step.
The main problem in the interaction is, as in CubeTEC Light, to handle the parts directly in the respot station without interrupting the ongoing production. Parts that are coming from an MFG station will interrupt the sequence of processes in the combined station.

**Figure 79 – Integration of an MFG station in CubeTEC Light+.**

### 10.5 CubeTEC: Complete Integration

A CubeTEC production system has complete separated areas for geometry operations and respot operations. The principle of driving from a geometry station to a respot station is the same principle as driving from an MFG station to a respot station. Figure 80 visualizes the interaction between an MFG station and the respot stations, described in Case A.3 in chapter 6.1.1. It will not require any changes in the hardware of the production system nor interrupting the sequence of the production. Nevertheless, an MFG station can also be integrated together with the current geometry station of CubeTEC, described in Case A.4 in chapter 6.1.1, and will in that case require the geometry stations in CubeTEC to hold a certain level of versatility for those operations.
Figure 80 – Integration of an MFG station in CubeTEC.
11 Discussion and Conclusions

In this chapter, the formulated research questions, stated in the introduction, are answered. This is followed by discussions regarding the proposed MFG station concepts and the integration scenarios. Finally, suggestions for further research are described.

11.1 Answers to Research Questions

The objective with this research was to eliminate the need for a complete reconstruction of a production line during integration of new car models in various production scenarios. The stated objective was followed by four research questions. From the main findings in this research, following research questions are answered:

RQ1 Can a new model within the C- and E-class architecture of platforms be integrated and produced in an MFG station?

Since the goal of an MFG station is to produce newly integrated car models, the answer is yes. Though, the level of changeability in an MFG station is the central factor for the usefulness of a station. The result from this research shows that a higher capacity will reduce the changeability. A versatile station will have to keep a high level of modularity, but with a low number of tool changes to maintain short cycle times. The versatility is directly related to new-model integration and is therefore considered as obligatory when new architectures rises.

However, an MFG station must also hold a certain flexibility for several GEO-steps and an alternated production between derivatives in a current model series. A flexible station can be assembled with flexible tools and consequently reduce footprint. The limiting factor for a flexible station is not related to how many robots or tools there are in a station. More, it is a combination of the whole system.

RQ2 Can an MFG station be placed in an existing or upcoming production scenario?

Yes, an MFG station can be placed in an upcoming production scenario as a supplement to a regular production line. An MFG station can produce a certain number of new geometries, for example the EV as a derivative in a current model series. An MFG station can be configured in different layouts and with different features depending on what type of production it has to encounter.
Integration of an MFG station in a modular production system, as for example CubeTEC, requires more adjustments than just integrating an MFG station. If the MFG station only interacts with the high flexible respot stations in the production system, the integration would be beneficial. The respot stations are considered to be flexible since no rigid fixtures are required. The bottleneck in the whole system in this case would be the respot stations. Additional respot stations are relatively simple to add for a sustained capacity in the system.

However, if the interaction is between both respot and geometry stations in the production system, the flexibility must be increased in the interacting conventional geometry stations. Figure 81 is describing what is required from the MFG station and the conventional GEO stations from one of the cases in Chapter 6.1. An MFG that can handle two GEO-steps of one derivative is considered to be flexible. Nevertheless, a conventional GEO station that has to interact with the MFG station must be able to produce one GEO-step of, at least, two derivatives. This forces the conventional GEO-stations to hold a high level of versatility to be able to reach the required flexibility. The projected problem in the interaction between an MFG station and conventional GEO stations is the integration of tools for the new model in the conventional GEO stations. Additionally, the bottleneck in such an integration would no longer be the respot stations. It would be the interacting geometry stations from the production system.

Figure 81 – Interaction between an MFG station and conventional GEO stations.
**RQ3**  **Can it be feasible to perform respot operations in an MFG station?**

Yes, for prototyping in a start-up factory where low volumes are produced in an MFG station, without a need for ramp up. However, it is not suitable to integrate respot operations for serial production. Due to high cycle times and consequently a low volume output, it will not be feasible to perform respot within an MFG station for serial production in high volumes. However, if the MFG station is integrated as independent and additional to a conventional line, the respot operations are mandatory to execute within the station.

**RQ4**  **Can an MFG station have the capacity to replace a number of less flexible geometry stations?**

Yes, the cycle time diagram for the SBS station is designed for each individual process to include tool changes with a preserved capacity of 7-18 jobs per hour. Nevertheless, a tool change is time consuming and should therefore be replaced with a flexible tool to minimize cycle time and increase capacity. However, it is necessary to balance the number of the variances to be manufactured in a station to how high the volumes of these should be. A station that produces assemblies in high volumes with low variation should have flexible tools. While a station that produces low volumes, but with a high variance of vehicles, should have flexible tools that can also be interchangeable.

### 11.2 Discussion

Flexibility is a commonly used expression for describing a station with high changeability. In this research, changeability is the overall expression for several terms. Flexibility and versatility are two of the most relevant to discuss. Flexibility is required for reaching versatility. But a station can hold a high level of flexibility without being versatile.

Final concepts are generated through a morphological table and link subjective assessments with objective measurements of changeability. The features in the morphological table are chosen upon what is considered to enable a high level of changeability. However, some features are still on a research stage or not yet possible to implement in a production due to too little research or high costs.

Systems with the highest level of changeability undergoes a high complexity. When material no longer is transported in sequence within one line, changeability is high, nor the complexity. Software for controlling must keep up with the high changeability of hardware in a station.
11.2.1 Comments on Developed Concepts

The SBS station from FFT is a well-developed concept for how an MFG station can take shape. The station is expandable for higher volumes and parallelization of workload. A high grade of automation enables the station to be put into serial production. However, an integration in the serial production requires the SBS station to hold a similar logistic principle as the production system to reach high capacity.

The concept “Low Footprint” is an optimization of the current SBS station. Industrial robots for handling operations in the concept “Low Footprint” are mounted on a second level on a gantry bridge. One is standing and one is hanging. The advantages with this principle is the high utilization of floor. However, the disadvantages with high-level mounted robots is the obstructed maintenance that has to be considered and evaluated. One of the main problems during conceptualization is to determine a reasonable size of the robots. A high-load robot requires an increased investment and limits the accessibility. In some cases, a high-load robot will be required for exchanging large and heavy parts or tools. Therefore, it is beneficial to develop lightweight grippers and fixtures for enabling a downgrade in robot size.

The concept “High Changeability A” holds a very high level of changeability in the station. The concept is the most suitable solution for the production of various geometries that are yet unknown, for example the EV. However, the station has a low capacity and a high footprint and may therefore not be applicable in a serial production.

The concept “High Capacity A” can produce high numbers of vehicles but holds a low changeability. When a certain derivative geometries and volumes are known and must be produced in higher volumes, the station can fulfil that. Nevertheless, it requires more footprint and the changeability is lower than other concepts.

The number of robots is strongly related to capacity and not to changeability. Parallelization of workload is required to maintain low cycle times. Tool changes is non-productive time. The non-productive time is also a part of the process time when cycle time analyses are executed. Since tools changes are more or less required to reach a high versatility in the station, the non-productive time must be parallelized. Additional robots can therefore increase capacity since they will enable a parallelization of non-productive time, as well as productive time in a station.
11.2.2 Contribution to Industry

For Daimler AG and for the industry, possible solutions to combine current and new technologies to reach a higher level of changeability has been concluded. Implementable sub-systems and alternatives for the production of EVs are requested by car manufacturers. An MFG station that holds a high level of changeability is one solution for the integration of EVs in a current production.

New production systems are at this time developed continuously by the industry; this research contributes with decision-making factors during this development. The solution of integrating new models in a current production is equally relevant to subcontractors as it is for Daimler AG.

11.2.3 Contribution to Academy

Literature regarding changeability expressions contain several interpretations of what it is. There are definitions that explain what will come out of the system, but not how. This research seeks how different changeability types can be transferred into hardware. The aim is to find what equipment designate a flexibility or versatility in individual components and in a system used for producing BiW-assemblies.

11.3 Conclusions

Table 17 is the result from Chapter 9 where the result from the concept analysis is presented. Conclusions regarding this are that a high changeability will demand more footprint. However, when focus is to minimize footprint, a high changeability can be still be achieved. High capacity can be obtained with a preserved or even increased changeability. The advantage of an MFG station that holds a high capacity is to be able to ramp up the production by adding components to the station.

The SBS station was concluded to have a medium to extended changeability according to the morphological analysis. By optimizing certain areas within the process or logistics of the SBS station, a higher level of changeability can be achieved. The concept “High Changeability A” is the optimum choice for utilizing a station for various models but still within the same capacity as the SBS station. The concept “High Capacity A” is an alternative that is more suitable for serial production due to a high capacity, but still with similar changeability as the SBS station.
The concept “High Capacity B” was concluded to have small differences compared to the SBS station. A capacity increase of only one job per hour to the drawback of slightly more footprint and less changeability. The concept “Low Footprint” showed to have even higher capacity, but with increases in changeability and decreases in footprint. Therefore should the concept “High Capacity B” not be an alternative during integration of an MFG station.

Commonly for all the presented concepts is to have common material transports performed by AGVs. The background for this is to have the MFG station integrated in a contemporary production scenario. Since a conventional BiW line does not utilize AGVs, the MFG station must work independently, to the drawback of a very low capacity. However, an MFG station that is integrated in a novel production scenario, like CubeTEC, can be scalable together with the production system. As a result, the production capacity can be alternated between ICEV and EV.

### 11.4 Suggestions for Further Research

In this research, several concepts for an MFG station are presented and discussed. For further development of the concepts, recommendations are listed in following bullets and described in succeeding paragraphs:

- Decide critical factors in a car-body production.
- Analyze different conditions for an integration.
- Develop modular interfaces for frozen zones.
- Determine when an MFG station should be deprived.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Process Changeability</th>
<th>Logistic Changeability</th>
<th>Capacity Jobs per Hour (CT)</th>
<th>Footprint (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS Station</td>
<td>3,68</td>
<td>3,25</td>
<td>7 (478)</td>
<td>169</td>
</tr>
<tr>
<td>High Changeability A</td>
<td>5,03</td>
<td>5,08</td>
<td>8 (450)</td>
<td>304</td>
</tr>
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<td>High Changeability B</td>
<td>4,03</td>
<td>4,50</td>
<td>10 (372)</td>
<td>191</td>
</tr>
<tr>
<td>High Capacity A</td>
<td>2,78</td>
<td>3,50</td>
<td>18 (198)</td>
<td>235</td>
</tr>
<tr>
<td>High Capacity B</td>
<td>3,48</td>
<td>3,19</td>
<td>8 (429)</td>
<td>191</td>
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<tr>
<td>Low Footprint</td>
<td>3,92</td>
<td>4,58</td>
<td>9 (418)</td>
<td>132</td>
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</table>
Decide the critical factors and make a trade-off between changeability, capacity and costs. Not only by comparing one-model production executed in alternative A or B. What is more relevant is to use a systems changeability in the calculations for a second lifecycle.

The morphological laboratory, together with the analysis in this research is on extreme cases. Each case must be analyzed based on different conditions. Every single concept must be optimized in changeability, capacity and footprint. To compare the concepts on a decision-taking level, a detailed economic evaluation must be performed.

When developing an MFG station, the interface of tools and equipment must be modular for exchange between robots and enable a scalability. Therefore, a common interface must be developed and settle as a frozen zone for the development of future production systems.

Integration of a new platform in a portfolio is rather simple. To produce it in today’s short lifecycles is complicated. The challenges that force a paradigm shift in the car production are reality. For this reason the production must be adaptable for those changes. It is beneficial to integrate a new derivative by implementing an MFG station instead of a completely new production system. An MFG station that can interact with a production system enables utilization over a second lifecycle. The aim of having an MFG station is the scalability that enables higher volumes during ramp-up phase. Nonetheless, it may not be profitable to expand an MFG station and continue producing by this concept. Therefore, it is essential to perform strategic and economic calculations along with an interpolated forecast to determine when it is profitable to deprive an MFG station and instead produce directly in a high-volume production system.

Finally, for further research it has to be concluded if it is the ability to produce several derivatives or to hold several GEO-steps that define a highly flexible geometry station.
List of References


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Weikelmann, A., 2018. *Daimler Internal Mitarbeiterportal*. [Online] Available at: https://portal.e.corpintra.net/wps/myportal/ut/p/a0/04_Sj9CPykssy0xPLMnMz0vMAfJigXRmkVVasVVBfnGJljbxiaGBfkG2oy1AoAeSeQ!!/[Accessed 5 April 2018].


Zäh, M. F., Möller, N. & Vogl, W., 2005. *Symbiosis of Changeable and Virtual Production – The Emperor's New Clothes or Key Factor for Future Success?*. München, s.n.

### Appendix 1: CT for High Changeability A

<table>
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<th>Code</th>
<th>Robot/Worker</th>
<th>Fixtures</th>
<th>Item</th>
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<th>Action</th>
<th>Comment</th>
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<table>
<thead>
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<th>Cycle time sheet High Changeability A</th>
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![Cycle time sheet](image-url)
### Appendix 2: CT for High Changeability B

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#### Cycle time sheet

- **High Changeability B**
- **Scaling:** 50,0 sec. per spacing
- **No. of pieces:** U/d

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#### High Changeability B Cycle Times

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### Additional Information

- **Calculation Details**
  - **Start**
  - **End**

#### Additional Notes

- **Use**
  - **Additional**
  - **Spa**

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**II**
## Appendix 3: CT for High Capacity A

### Cycle time sheet

**High Capacity A**

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<th>Stress</th>
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### No. of pieces: 

### U/d

### Code Robot/Worker Fixtures time Health Comment Lead time Start Time Stress

### High Capacity A

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<th>Time</th>
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### No. of pieces:

### U/d

### Code Robot/Worker Fixtures time Health Comment Lead time Start Time Stress

### Cycle time sheet

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### High Capacity A

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### Scale: 40,0 sec. per spacing

### No. of pieces:

### U/d

### Code Robot/Worker Fixtures time Health Comment Lead time Start Time Stress

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<th>Robot/Worker</th>
<th>Fixtures</th>
<th>Time</th>
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### High Capacity A

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### U/d

### Code Robot/Worker Fixtures time Health Comment Lead time Start Time Stress

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### High Capacity A

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### Scale: 40,0 sec. per spacing

### No. of pieces:
Appendix 6: CT for High Changeability A + Respot

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<th>Code Robot/ Worker</th>
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Cycle time sheet
High Changeability A + RS

Cycle time sheet Scaling: 50,0 sec per spacing
High Changeability A + RS

Start | No. of pieces: U/d | Code Robot/ Worker | Comment |
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<tbody>
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</tbody>
</table>

Summary:
- Start: ...
- No. of pieces: ...
- Code Robot/ Worker: ...
- Comment: ...

VI
Appendix 7: CT for High Changeability B + Respot

<table>
<thead>
<tr>
<th>Cycle time sheet</th>
<th>High Changeability B + RS</th>
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<tbody>
<tr>
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- **Functional Purpose:**
- **To be implemented:**
- **High Changeability B + Respot**

**Notes:**
- **Start and End Times:**
- **Functional Operations:**
- **Related to:**
- **References:**
Appendix 8: CT for High Capacity A + Respot

| Cycle sheet | High Capacity A + Respot |

<table>
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<tr>
<td>IRB_700</td>
<td>10RB_100</td>
<td>10RB_600</td>
<td>IRB PLACES ZB IN FIXTURE</td>
</tr>
<tr>
<td>IRB_700</td>
<td>10RB_100</td>
<td>10RB_600</td>
<td>IRB MOVES TO AGV (SP)</td>
</tr>
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<td>RS_23XSPR</td>
<td>10RB_600</td>
<td>10RB_100</td>
<td>TOOL CHANGE - RSW TO SPR</td>
</tr>
<tr>
<td>IRB_700</td>
<td>10RB_100</td>
<td>10RB_600</td>
<td>IRB MOVES TO FIXTURE (GEO 1)</td>
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<td>IRB PLACES SP IN FIXTURE</td>
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<tr>
<td>JOINING 3 X SPR</td>
<td>10RB_600</td>
<td>10RB_100</td>
<td>IRB PLACES SP IN FIXTURE</td>
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<tr>
<td>IRB_700</td>
<td>10RB_100</td>
<td>10RB_600</td>
<td>IRB TAKES SP FROM AGV (SP)</td>
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<tr>
<td>JOINING 2 X SPR</td>
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<td>FIXTURE CLAMPS</td>
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Cycle time sheet Scaling: 40.0 sec per spacing
High Capacity A + RS No of pieces: U/d
Code Robot/Worker Fixtures.../10RB_400 0 0 RS 24 X SPR x 1,0 84,0 305,7 84,0 389,7
40,0 80,0 120,0 160,0 200,0 240,0 280,0 320,0 360,0 400,0
Appendix 9: CT for High Capacity B + Respot