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Production Resource Flexibility Assessment: Case Studies in the Automotive Industry

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Abstract

The automotive industry is characterized by a high degree of uncertainty. Companies are facing the challenge of producing different systems simultaneously. Additionally, the global quantity of electric vehicles is also expected to increase significantly. This results in the following capability to remain competitive: Effective and efficient adaptions of production systems to model variations and volume increases. While flexible production is identified as the most promising concept, defining the actual flexibility level of included production resources is essential for its proper realization. A literature review on existing flexibility assessment approaches revealed their emphasis on high-level enablers and limited practical applicability in the automotive industry. In contrast, focusing the assessment on single workstations supports the selection of appropriate production resources. Therefore, a simple and structured standard procedure for a production resource flexibility assessment was developed. This theoretical construct was subsequently complemented with practical insights through its application on two real-life case studies within one automotive engineering company. Summarizing and discussing the findings in combination with a conclusion completed this paper.

Keywords

Production Flexibility, Production Resource, Flexibility Assessment, Automotive Industry.

Introduction

Already in the previous millennia, the automotive market was described as volatile with constantly new customer demands (Siddique et al. 1998). According to Berger and Lazard (2017), current major trends comprising new mobility business models, autonomous driving, digitalization and electrification are accelerating disruptions in the industry. Comparing different automotive domains, their recent study also identified a particularly high impact for powertrain systems. Additionally, future powertrains are predicted to be electrified, which results in several fast-growing areas including power electronics, e-axles, battery packs, and more (Berger & Lazard, 2017).

The rise of e-mobility and the transition from conventional to electrified powertrains is rather slow. Therefore, automotive companies are facing the challenge of producing, selling, and servicing different systems simultaneously (Küpper et al., 2018). Meeting the varying customer desires also leads to a growing product portfolio. Recent announcements of automotive OEMs about new electric car models from the Global EV Outlook 2021 are shown in Table 1 and underline this trend. It outlines that the variety of electric cars is expected to increase significantly in the upcoming years (International Energy Agency, 2021). This results in the first required capability of automotive OEMs to remain competitive: Effective and efficient adaptions of production systems to model variations.

Besides their diversification, the quantity of electric vehicles (EVs) is also expected to grow. The Global EV Outlook 2021 considered two situations, the "stated policies scenario", reflecting all policies

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Table 1
OEM's announcements about electric cars

OEM	Announcements
BMW	25 new models by 2023
Ford	40 new models by 2022
Daimler	10 new models by 2022
Renault–Nissan–Mitsubishi	20 new models by 2022
Toyota	15 new models by 2025
Volkswagen	75 new models by 2029

that had already been announced by governments around the world, and the "sustainable development scenario", assuming the achievement of global climate goals in line with the Paris agreement as well as all EV sales targets. Between 2020 and 2030, the stated policies scenario demonstrates a rise from 11.3 to 142.7 million EVs worldwide. In contrast, the fleet size even reaches 230 million in the sustainable development scenario (International Energy Agency, 2021). While the actual numbers remain unknown, a significant increase is highly probable. Due to this predicted acceleration, the annual production volume of EVs must also rise. This results in the second required capability of automotive OEMs to remain competitive: Effective and efficient adaptions of production systems to volume increases.

Literature review

Coping with production changes

Among the numerous terms in current literature, the most prominent concepts for production companies to cope with changes are flexibility, transformability, and agility (Wiendahl & Hernandez, 2002). These concepts are often summarized under the term changeability, which describes the "*ability to accomplish early and foresighted adjustments of the factory's structures and processes on all levels to change impulses economically*". The characteristics of flexibility, transformability, and agility can be differentiated as follows (Wiendahl et al., 2007):

- Flexibility: ability of a production and logistics area to switch with little cost and time to new but similar component families by changing manufacturing processes, material flows, and logistic functions.
- Transformability: ability of a production site to switch to another product family. This requires adaptations of the production and logistics systems, the building facilities, the organization, and the staff.

- Agility: ability of an entire company to open up new markets, to develop the requisite products and services, and to build up necessary manufacturing capacity.

Based on their detailed comparison, flexible production is identified as the most promising concept to realize effective and efficient adaptions of production systems to model variations and volume increases for automotive manufacturers.

Production flexibility assessment

Metternich et al. (2013) argue that increasing the flexibility often results in higher costs. Intending to optimize the economic situation of a company means that its production system should be only as flexible as necessary (Metternich et al., 2013). Tolio (2009) provides methods to identify the optimal trade-off between flexibility and productivity. Having identified the required flexibility level (To–Be), the next step deals with its realization. Several studies have investigated enablers for flexibility. Typical key domains include the production system (preventive maintenance, manufacturing technology, etc.), its operators (multi-skilled workforce, workforce flexibility, etc.), and the product design (DFX guidelines, modular product architecture, etc.) (Hallgren & Olhager, 2009; Olhager & West 2002; Scherrer-Rathje et al., 2014, Ulrich, 1995).

In order to achieve a specific target (To–Be), also the initial situation (As–Is) must be defined. This approach is in accordance with the three steps presented by Suarez et al. (1991): (1) identifying the need for flexibility; (2) implementing flexibility; (3) fitting between required and actual flexibility. Therefore, assessing the actual flexibility level of available but also potential production resources combined with its comparison to the required level as shown in Figure 1 represents the basis. The aim is clearly the effective and
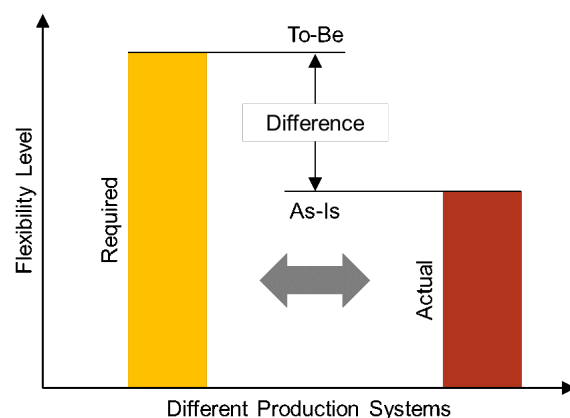

Fig. 1. Overall control structure

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efficient minimization of the identified difference. Any remaining deviation leads to an unsatisfying result. In case the actual level is smaller than the required level, the production system cannot cope with all potential changes. On the other hand, a greater flexibility level indicates unnecessary costs that could have been saved.

Heimes (2014) presents a potential approach to identify appropriate production resources for current challenges in the automotive industry, especially battery packs. The selection is based on five requirements: maturity, quality, cost, throughput, and flexibility. Furthermore, their required and actual levels are quantified between 0–5, and subsequently visualized on a common radar chart. This enables a simple and quick identification of under, exactly, or over fulfilled requirements. Nevertheless, no actual method for the quantification of the flexibility level is described or applied transparently. Mishra et al. (2014) also conducted a comprehensive review on the assessment of manufacturing flexibility. Having investigated numerous frameworks, the authors argue that they mainly emphasize on management and implementation aspects. Besides the proposal of a conceptual framework to assess the flexibility level of an organization, a clear description or application to achieve quantitative results is still missing. Palani et al. (2003) and Keese et al. (2006) present approaches to identify critical changes, where the readiness of the manufacturer to cope with them represents one of the determining factors. While a quantification between 0–10 is suggested, details about the evaluation of production systems or resources are not included. The authors argue instead that each manufacturer must create an own rating system due to the varying information. Lafou et al. (2015) investigated factors to quantify product flexibility to support decisions for manufacturing system designers. Joseph and Sridharan (2011) used simulation modelling to evaluate routing flexibility. Similarly, Sahay and Ierapetritou (2015) applied a simulation-based framework for the assessment of flexibility in supply chains. Since Zhong (2015) considered production and transportation, the framework differentiates between three main categories: manufacturing flexibility, logistic flexibility, and system flexibility. The procedure was applied on a case study about Louis Vuitton stores. Nevertheless, this broad view is not in accordance with the scope of production flexibility as defined in the currently presented work. Son and Park (1987) suggest four types of flexibility measures: equipment flexibility, product flexibility, process flexibility, and demand flexibility. The authors claim that only a total flexibility measurement allows optimizing the opportunities for a com-

pany. Gupta and Somers (1992) encourage the application of a standard instrument for measuring manufacturing flexibility on the production system level. Florescu and Barabaş (2017) as well as Ervural et al. (2019) dealt with decision supports to optimize flexible production systems. Calvo et al. (2003) followed an integrated assessment of manufacturing flexibility, covering several areas such as machinery, human resources, process, product mix, operation, routing, volume, and expansion. While formulas for the quantification of each flexibility type are provided, the result is rather superficial. Focused on a more detailed level, Ali and Murshid (2016) investigated the performance evaluation of flexible manufacturing system under different material handling strategies. Wahab and Osman (2013) as well as Chang et al. (2001) focused on machine flexibility. Including several detailed factors for their assessment, these approaches seem useful but not completely sufficient for the selection of appropriate production resources to realize the required flexibility level.

Research gap

Since available flexibility assessment approaches strongly emphasize on high-level enablers, they provide only limited support for the selection of production resources. Furthermore, their practical applicability in the automotive industry seems also rather limited. Breaking down the focus of flexibility assessments from the entire production system to single workstations represents a suitable solution.

Research questions

1. How can the flexibility of single workstations be simply but objectively assessed?
2. What are appropriate criteria for a flexibility assessment in the automotive industry?

Production resource flexibility assessment

Assessment procedure

Along a general supply chain, the used definition of flexibility narrows down the focus to the production site. Since only the underlying resources of single workstations are of interest, another breakdown is necessary. Taking a closer look at the basic elements of production systems (Gudehus and Kotzab, 2012; Boothroyd et al., 2002), this paper concentrates on manufacturing and assembly operations in a combined

manner as the authors believe they cover the greatest potential for improvements. The three elementary production factors from Gutenberg (1951), namely operating equipment, material and labour, represent the basis upon which the simple but objective flexibility assessment is built. Figure 2 illustrates an overview of the system definition.
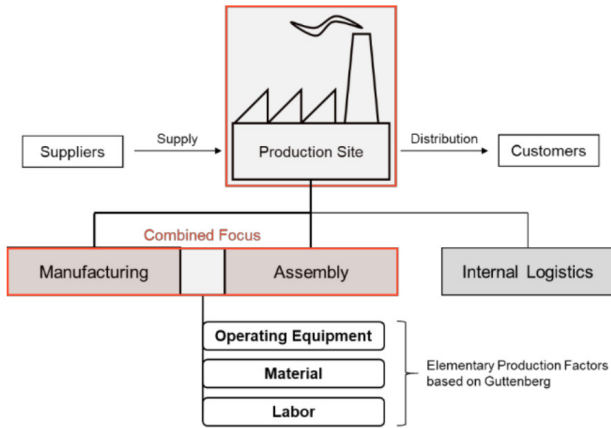

Fig. 2. System definition

The procedure of the developed production resource flexibility assessment was inspired by the agility index from Rabitsch (2016). In this work, the agility level is assessed based on the individual rating of specific criteria between least, moderate, and most. Allocating numbers to each criterion allows the quantification of an overall level. The previously presented three elementary production factors are the foundation of the criteria for the production resource flexibility assessment. Figure 3 illustrates sample results based on the operating equipment factor. Nevertheless, the developed assessment procedure does not provide an absolute measure of flexibility. Based on the previously de-
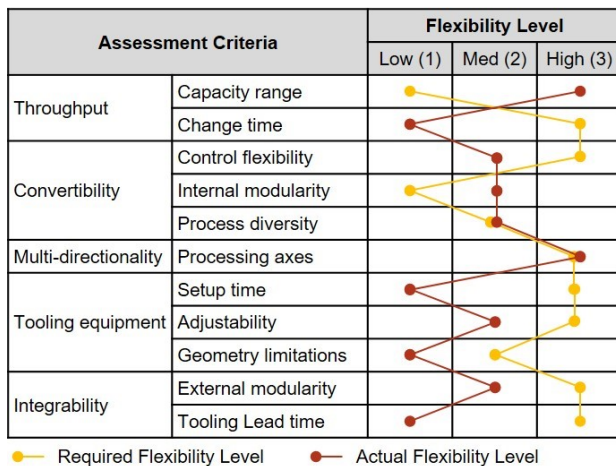
scribed aim of minimizing the difference between the required and actual flexibility level, relative assessments are fully sufficient. This requires a common rating system. The mutual visualization of the required and actual flexibility level as shown in Figure 3 allows decision maker to easily and quickly identify gaps as well as to understand factors or areas that need further attention. Additionally, not only the flexibility of one but several production resources can be simultaneously integrated in one graph. An applicability on manual, automated, and hybrid production workstations is necessary to ensure a sufficient generalization of results.

Assessment criteria

The three elementary production factors operating equipment, material, and labor are the foundation for the production resource flexibility assessment. Following the requirements stated before, the aim is to identify a comprehensive list of assessment criteria including an appropriate rating system. Two pillars, a literature review and an idea generation workshop, built the basis upon which this was realized. The assessment criteria, their category, and source are shown in Table 2, Table 3, and Table 4 respectively for the

Fig. 3. Sample production resource flexibility assessment

Table 2
Flexibility assessment – Operating equipment

Category	Assessment criteria	Source
Capacity Flexibility	Range of production capacity [#/time]	Gerwin, 1987
	Time to change between lowest and highest capacity [time]	Chen et al., 1992
Convertibility	Control flexibility (Automated Station: AS; Manual Station: MS)	Azab et al., 2003
	Internal modularity of production equipment	Sethi and Sethi, 1990
	Number of performable manufacturing processes [#]	Authors
Multi-directionality tooling equipment	Number of processing axes [#]	Maier-Speredelozzi et al., 2003
	Setup time [time]	Posteuca et al., 2015
	Adjustability for multiple purposes	Ulrich, 1995
	Geometry limitations	Authors
	Weight limitations	Authors
Integrability	External modularity of production equipment	Authors
	Tooling Lead Time	Bralla, 1999

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Table 3
Flexibility assessment – Material

Category	Assessment criteria	Source
Handling Equipment (gripper, jig, etc.)	Adjustability for shape variations	Chakraborty et al., 2006
	Setup time [time]	Posteuca et al., 2015
	Geometry limitations	Authors
	Weight limitations	Authors
Availability	Availability of parts and material	Beach et al., 2000
Transport	Transportation method	Chakraborty et al., 2006
	Transportation speed	Authors
Quality	Change of quality with increasing volume	Authors

Table 4
Flexibility assessment – Labour

Category	Assessment criteria	Source
Task flexibility	Experience	Authors
	Education	Michalos et al., 2010
Availability	Dealing with changing demand in workforce / Workforce flexibility	Rabitsch, 2016
Reliability	Change of quality with different work extent: e.g. work under pressure	Michalos et al., 2010

three production factors operating equipment, material, and labor.

Basically, qualitative and quantitative methods can be distinguished. While the qualitative rating relies on three different statements, the quantitative rating is based on normalizations and three different number ranges, for instance: 0–0.32 / 0.33–0.66 / 0.67–1. The results of each criterion are further translated into the same flexibility rating scheme: low (= 1); medium (= 2); and high (= 3). Quantitative criteria are further differentiable between beneficial (the grater the value, the better the alternative) and non-beneficial (the smaller the value, the better the alternative). Sample formulas for the normalization of two criteria are demonstrated here:

Beneficial: e.g. Number of processing axes

$$\text{Axes}_{\text{Norm}} = \frac{\text{Num}_{\text{ACTUAL}} - \text{Num}_{\text{MIN}}}{\text{Num}_{\text{MAX}} - \text{Num}_{\text{MIN}}} \quad (1)$$

Non-beneficial: e.g. Setup time

$$\text{Setup}_{\text{Norm}} = \frac{\text{Time}_{\text{MAX}} - \text{Time}_{\text{ACTUAL}}}{\text{Time}_{\text{MAX}} - \text{Time}_{\text{MIN}}} \quad (2)$$

Depending on the investigated workstations, all reasonable criteria of the three factors should be applied for their production resource flexibility assessment. Nevertheless, not all are always appropriate due to the unique characteristics of different project. In case the applied criteria vary, only results with the same are directly comparable.

Practical insights

Research approach

A single case design was chosen due to the uniqueness of the case (Yin, 2009) as well as the opportunity for a greater depth of observation (Voss et al., 2016). It was represented by a worldwide leading engineering company in the automotive industry, AVL List GmbH. This company mainly deals with the development of entire powertrain systems and their elements such as internal combustion engines, battery packs, transmissions, and more. In addition, several projects concerning the actual production have already been conducted. Since an investigation of entire powertrain systems seems rather complex with the risk of attaining superficial results, the focus was narrowed down to the included elements. As previously described, especially the rise of e-mobility causes critical changes in the automotive industry. This led to the selection of two different units of analysis in this field for detailed investigations: A (battery module assembly) and B (electric axle assembly). Within each case, a single workstation of a specific process step was selected to apply the production resource flexibility assessment. According to Yin (2009), integrating multiple units of analysis also provides advantages, such as improved generalization, reduced observer bias, and enhanced insights. Figure 4 provides an overview of the applied
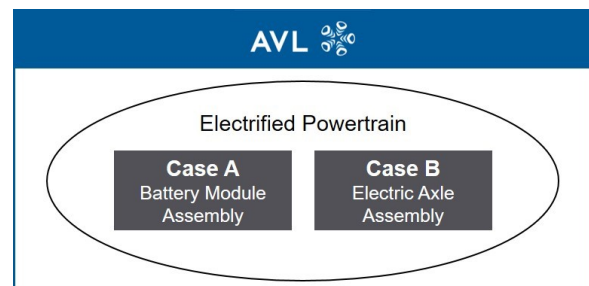

Fig. 4. Case study design

case study. Having completed its design, the time-frame must be subsequently defined. Due to the easier access of data and improved planning activities (Yin, 2009), investigating retrospective cases was chosen.

A – Battery Module Assembly

Fundamental theory

The reason for the upswing of e-mobility is a more efficient design of the energy storage in vehicles. Lithium-ion technology has established for traction batteries, where new and better concepts are constantly explored Wallentowitz, 2013). Therefore, the automotive industry must plan production systems that are flexible to innovations and changes in the future. Due to the different structures and formats of battery cells (cylindrical, prismatic, pouch), automobile manufacturers are faced with their selection already at an early development stage (Kirschner et al., 2021). Since battery cells are constantly evolving, it is generally difficult to predict which type will prevail (Hettesheimer et al., 2017).

In order to be used for e-mobility, battery cells are connected in serial and parallel to meet the performance requirements. Such an interconnection is achieved by assembling the cells with bus bars to form battery modules and battery packs (Korthauer, 2013). Focusing on the battery module assembly process, seven steps can be differentiated: 1) incoming inspection; 2) stacking of cells; 3) bus bar connection; 4) attaching BMS board & sensors; 5) assembly of cooling plates; 6) assembly of housing; 7) End-of-Line test (Kampker, 2014). Aiming to realize the required flexibility, each individual step must be thoroughly investigated. The following production resource flexibility assessment is described on the basis of the sub-process "quality assurance at the stacking station". This ensures traceability and demonstrates that the assessment can be applied at any level of detail.

Use cases from practice

At AVL List GmbH, a new project called "Battery Innovation Center" (BIC) is currently conducted. The BIC represents a facility that allows the assembly of both, conceptual and production-ready high-voltage battery prototypes using automated manufacturing technologies. It provides a relevant R&D platform in the automotive industry to strengthen and improve innovations as well as competencies along the entire value chain in the e-mobility sector. At the BIC, an incoming quality control for battery cells is implemented before they are assembled into modules and packs. In this context, four concepts (Table 5) with different flexibility levels were defined. They represent a step-by-step scaling to check different cell types and formats.

Table 5
Comparison of the four concepts

Concept	# of Cell Types	# of Cell Formats	Flexibility
A	1 (cylindrical)	1	lowest
B	1 (cylindrical)	all	low
C	2 (prismatic & Pouch)	all	high
D	3 (all)	all	highest

Flexibility assessment

Since this assessment compares different concepts relatively to each other, a normalization of quantitative criteria is necessary as previously described (Formula (1) and Formula (2)). Therefore, the maximum and minimum value of each quantitatively measurable criterion have to be defined. On the other hand, an example of a qualitative criterion is "control flexibility". If the modification from one production process to another can be done with basic programming skills, the solution is classified as "highly" flexible. A more sophisticated programming decreases the flexibility, which leads to the flexibility level medium. In case there is no possibility of reprogramming, the flexibility is classified as "low".

Table 6 presents an overview of the production resource flexibility assessments of all four concepts. As expected, concept A where only cylindrical cells are tested, is the most rigid solution with a relative flexibility value of 1.41. In comparison, the flexibility in concept B increases to 1.73. Considering concept C that enables the inspection of pouch and prismatic cells, a jump to 2.45 occurs. Concept D appears as the most flexible solution with a flexibility level of 2.64. With the increasing variety of battery cell formats, the requirements on equipment and operating staff also rise. In general, the use of robotics as well

Table 6
Comparison of the assessment results

Domains	Concept A	Concept B	Concept C	Concept D
Operating equipment	1.18	1.64	2.55	2.73
Material / Parts	1.43	1.71	2.29	2.57
Labour	2	2	2.5	2.5
Average	**1.41**	**1.73**	**2.45**	**2.64**

as more experienced and educated operators lead to a higher flexibility level. Finally, it can be argued that the defined criteria including their rating system were suitable. The application of the production resource flexibility assessment was rather simple and delivered the expected results, supporting the proof of method objectivity. As already mentioned, the flexibility levels are not absolute but relative to each other. Therefore, changing the production resources directly impacts the assessment results.

B – Electric Axle Assembly

Fundamental theory

The electric axle (e-axle) is a component of the electrified powertrain. The e-axle can be further divided into the energy and torque conversion system. In addition, the energy conversion system consists of the electric motor (EM), the inverter, and the electric control unit (ECU) (Abdul Hadi et al., 2021). The already huge variety of EV models on the market is expected to increase further. These varieties also result in different e-axles with respect to individual needs and automotive suppliers. Due to the small batch size and high model variety of e-axles, building a flexible assembly line that allows effective and efficient adaptions is essential to remain competitive. This also requires the selection of appropriate production resources.

Use cases from practice

Figure 5 illustrates a potential layout that can adapt to the increasing variety of e-axles. It comprises seven stations, each with specific tasks related to their assembly. Within this paper, the production resource flexibility assessment is only applied on the closing station (5) because it was identified as most crucial. Three main tasks are performed there: 1) applying the sealant; 2) closing the left and right housings; and 3) bolting operations for the housings. The tasks of the closing station are typically performed manually. Nevertheless, three alternative concepts are possible:

    A. manual assembly station;
    B. adaptive assembly station;
    C. completely automated assembly station.

When the tasks of the closing station are performed manually, it consumes over 240 seconds as compared to adaptive assembly stations with 40–60 seconds. Therefore, huge time savings are possible along with higher quality. The manual assembly is also prone to human errors due to higher variety and complexity. This can be prevented when adaptive concepts are integrated into the assembly line. On the other hand, also a fully automated assembly station might be considered. Nevertheless, the higher investment costs and low production volume of e-axles expand the amortization period. Furthermore, as models keep varying constantly, an automated system needs huge efforts in programming to cover a certain flexibility level.

Flexibility assessment

The final step is the application of the production resource flexibility assessment on the three concepts of the closing station. This was performed in the same manner as case study A. An overview of the results is presented in Table 7. They underline that having an adaptive assembly station is an ideal solution for the high variety and low batch size production of e-axles. Furthermore, the manual assembly station also
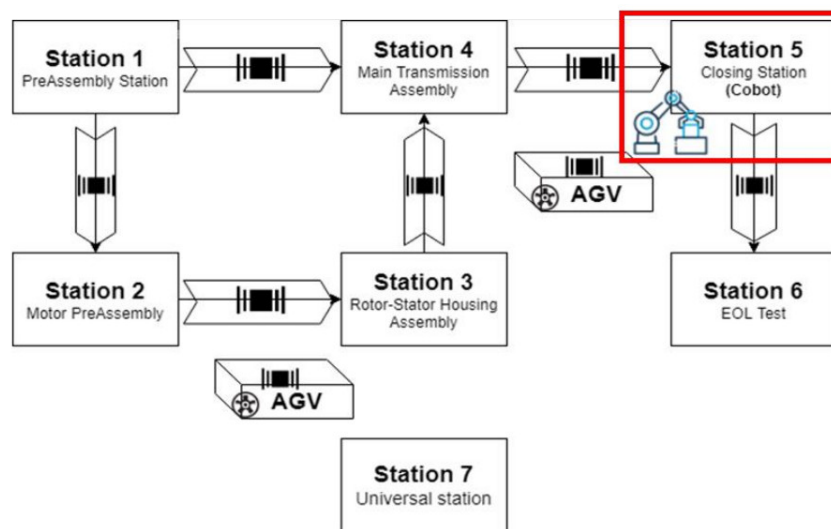

Fig. 5. Focus of case study B within e-axle assembly line

provides a rather high flexibility level compared to a completely automated station as expected. These results allow claiming that the defined assessment criteria including their rating system were appropriate. Furthermore, the authors also evaluated that the application of the developed production resource flexibility assessment was simple and objective.

Table 7
Comparison of the assessment results

Domains	Concept A	Concept B	Concept C
Operating equipment	2.24	2.44	1.57
Material / Parts	2.15	2.21	1.71
Labour	1.4	1.8	1.2
Average	1.93	2.15	1.49

Summary and conclusion

The automotive industry is characterized by a high degree of uncertainty. Two capabilities are required to remain competitive: Effective and efficient adaptions of the production systems to model variations and volume increases. Flexible production was identified as the most promising concept for their realization. A detailed literature review on available flexibility assessment approaches revealed the need for a more simple and objective procedure focused on single workstations. Therefore, a production resource flexibility assessment addressing this challenge was developed. The three elementary production factors operating equipment, material, and labour represent its foundation. All criteria and their corresponding rating system were built upon a literature review and idea generation workshops.

This theoretical construct was subsequently complemented with practical insights through its application at AVL List GmbH. In order to enable a detailed investigation, two units of analysis in the e-mobility sector were selected: A (battery module assembly) and B (electric axle assembly). Within each unit of analysis, the production resource flexibility assessment was applied on a single workstation of a specific process step. Furthermore, different concepts were investigated and compared. Those that were already excepted to be more flexible also delivered the highest flexibility levels. This allowed arguing that the defined criteria and their rating system for the assessment are appropriate. Even though the application of the production resource flexibility assessment might seem trivial at first, it finally enabled a simple and objective quantification for single workstations in the automotive industry. Therefore, both research questions were answered.

Nevertheless, the flexibility level should not be the only factor that determines the selection of production resources. The work of Heimes (2014) suggests the identification of appropriate production resources in the automotive industry based on five requirements: maturity, quality, cost, throughput and flexibility. While their required and actual levels are quantified between 0–5, actual procedures were not described or applied transparently. The presented work finally addresses this challenge through a simple and objective production resource flexibility assessment including two detailed applications. Subsequently, the values of all five requirements can be visualized on a common radar chart to enable a quick identification of under, exactly or over fulfilled areas. It is important to mention that the values of the production resource flexibility assessment cannot always be clearly defined and require a certain expertise. Some estimations depend on the knowledge from previous projects. In general, the assessments of the criteria should be conducted with a group that sufficiently covers a broad and diverse field of expertise.

References

Abdul Hadi M., Brillinger M. and Weinzerl M. (2021), Parametric evaluation and cost analysis in an e-axle assembly layout, *Proceedings of the 5th EAI International Conference on Management of Manufacturing Systems*, pp. 39–55.

Ali M. and Murshid M. (2016), Performance Evaluation of Flexible Manufacturing System Under Different Material Handling Strategies, *Global Journal of Flexible Systems Management*, No. 3, Vol. 17, pp. 287–305.

Azab A., Elmaraghy H., Nyhuis P., Pachow-Frauenhofer J., and Schmidt M. (2013), Mechanics of change: A framework to reconfigure manufacturing

systems, *CIRP Journal of Manufacturing Science and Technology*, Vol. 6, pp. 110–119.

Beach R., Muhlemann A.P., Price D.H.R., Paterson A., and Sharp J.A. (2000), A review on manufacturing flexibility, *European Journal of Operational Research*, No. 1, Vol. 122, pp. 41–57.

Berger R. and Lazard (2017), *Global Automotive Supplier Study 2018*, available at https://www.roland berger.com/en/Insights/Publications/Global-Auto motive-Supplier-Study-2018.html.

Bi Z.M., Lang S.Y.T., Shen W., and Wang L. (2008), Reconfigurable manufacturing systems: The state of the art, *International Journal of Production Research*, No. 4, Vol. 46, pp. 967–992.

Boothroyd G., Knight W., and Dewhurst P. (2002), *Product Design for Manufacturing Assembly*, Marcel Dekker, United States of America.

Bralla J.G. (1996), *Design for Excellence*. Technicraft Publishers, United States of America.

Calvo R., Domingo R., and Sebastián M.A. (2003), An Integrated Assessment of Manufacturing Flexibility, *Journal for Manufacturing Science and Production*, No. 3, Vol. 5, pp. 151–161.

Chakraborty S. and Banik D. (2006), Design of a material handling equipment selection model using analytic hierarchy process, *International Journal of Advanced Manufacturing Technologies*, Vol. 28, pp. 1237–1245.

Chang A-Y., Whitehouse D.J., Chang S-Y., and Hsieh Y-C. (2001), An approach to the measurement of single-machine flexibility, *International Journal of Production Research*, No. 8, Vol. 39, pp. 1589–1601.

Chen I.J., Calantone R.J., and Chung C.H. (1992), The Marketing-Manufacturing Inter-face and Manufacturing Flexibility, *International Journal of Management Science*, No. 4, Vol. 20, pp. 431-443.

Ervural B.C., Ervural B., and Kabak Ö. (2019), Evaluation of Flexible Manufacturing Systems Using a Hesitant Group Decision Making Approach, *Journal of Intelligent Systems*, No. 2, Vol. 28, pp. 245–258.

Florescu A. and Barabaş S.A. (2017), Decision models in designing flexible production systems, *MATEC Web of Conferences*, Vol. 94, pp. 1-8.

Gerwin D. (1987), An Agenda for Research on the Flexibility of Manufacturing Processes, *International Journal of Operations & Production Management*, No. 1, Vol. 7, pp. 38–49.

Gudehus T. and Kotzab H. (2012), *Comprehensive Logistics*, Springer, London.

Gupta Y.P. and Somers T.M. (1992), The measurement of manufacturing flexibility, *European Journal of Operational Research*, Vol. 60, pp. 166–182.

Gutenberg E. (1951), *Grundlagen der Betriebswirtschaftslehre: Die Produktion*, Springer, Germany.

Hallgren M. and Olhager J. (2009), Flexibility configurations. Empirical analysis of volume and product mix flexibility, *Omega*, No. 4, Vol. 37, pp. 746–756.

Heimes H.H. (2014), *Methodik zur Auswahl von Fertigungsressourcen in der Batterieproduktion*, PhD Thesis, RWTH Aachen University.

Hettesheimer T., Möller K.C., Wolter M., Lorentz V., Wenger M., Prill T., Zausch J., et al. (2017), *Entwicklungsperspektiven für Zellformate von Lithium-Ionen-Batterien in der Elektromobilität*, Fraunhofer-Allianz Batterien, Fraunhofer, Germany.

International Energy Agency (2021), *Global EV Outlook 2020 – Accelerating ambitions despite the pandemic*, available at https://www.iea.org/reports/global-ev-outlook-2021.

Joseph O.A. and Sridharan R. (2011), Evaluation of routing flexibility of a flexible manufacturing system using simulation modelling and analysis, *International Journal of Advanced Manufacturing Technology*, Vol. 56, pp. 273–289.

Kampker A. (2014), *Elektromobilproduktion*, Springer, Aachen.

Keese D.A., Takawale N., Seepersad C., and Wood K.L. (2006), An enhanced change modes and effects analysis (CMEA) tool for measuring product flexibility with applications to consumer products, *Proceedings ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, pp. 1–16.

Kirschner C., Moerth-Teo O., and Ramsauer C. (2021), Zukunftsperspektive von Lithium-Ionen-Batteriepacks: Erörterung von Trends, Herausforderungen und Unsicherheiten der Produktion, *Zeitschrift für wirtschaftlichen Fabrikbetrieb – Elektromobilität*, No. 11, Vol. 116, pp. 788–791.

Korthauer R. (2013), *Handbuch Lithium-Ionen-Batterien*, Springer, Frankfurt.

Küpper D., Sieben C., Kuhlmann K., and Ahmad J. (2018), *Will Flexible-Cell Manufacturing Revolutionize Carmaking?*, available at https://www.bcg.com/publications/2018/flexible-cell-manufacturing-revolutionize-carmaking.aspx

Lafou M., Mathieu L., Pois S., and Alochet M. (2015), Manufacturing System Flexibility: Product Flexibility Assessment, *Procedia CIRP*, Vol. 41, pp. 99–104.

Maier-Speredelozzi V. and Koren Y. (2003), Convertibility Measures for Manufacturing Systems, *CIRP Annals*, No. 1, Vol. 52, pp. 367–370.

Metternich J., Böllhoff J., Seifermann S., and Beck S. (2013), Volume and Mix Flexibility Evaluation of Lean Production Systems, *Procedia CIRP*, Vol. 9, pp. 79–84.

Michalos G., Makris S., Papakostas N., Mourtzis D. and Chryssolouris G. (2010), Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach, *CIRP Journal of Manufacturing Science and Technology*, No. 2, Vol. 2, pp. 81–91.

Mishra T., Pundir A.K., and Ganapathy, L. (2014), Assessment of manufacturing flexibility, *Management Research Review*, No. 8, Vol. 37, pp. 750–776.

Olhager J. and West B.M. (2002), The house of flexibility. Using the QFD approach to deploy manufacturing flexibility, *International Journal of Operations & Production Management*, No. 1, Vol. 22, pp. 50–79.

Palani R.P.K, Van Wie M., and Campbell M. (2003), *Design for Flexibility – Measures and Guidelines*, paper presented at the International Conference on Engineering Design, 19-21 August, Stockholm.

Posteuca A. and Zapciu M. (2015), Setup time and cost reduction in conditions of low volume and overcapacity, *UPB Scientific Bulletin, Series D: Mechanical Engineering*, No. 4, Vol. 77, pp. 325–336.

Rabitsch C. (2016), *Methodology for Implementing Agility in Manufacturing Companies*, PhD thesis, Graz University of Technology.

Sahay N. and Ierapetritou M. (2015), Flexibility assessment and risk management in supply chains, *Process Systems Engineering*, No. 12, Vol. 61, pp. 4166–4178.

Scherrer-Rathje M., Deflorin P., and Anand G. (2014), Manufacturing flexibility through outsourcing. Effects of contingencies, *International Journal of Operations & Production Management*, No. 9, Vol. 34, pp. 1210–1242.

Sethi A.K. and Sethi S.P. (1990), Flexibility in Manufacturing: A Survey, *International Journal of Flexible Manufacturing Systems*, Vol. 2, pp. 289–328.

Siddique Z., Rosen D.W., and Wang N. (1998), *On the applicability of product variety design concepts to automotive platform commonality, Proceedings of the Design Engineering Technical Conferences*.

Son Y.K. and Park C.S. (1987), Economic measure of productivity, quality, and flexibility in Advanced Manufacturing Systems, *Journal of Manufacturing Systems*, No. 3, Vol. 6, pp. 193–206.

Suarez F.F., Cusumano M.A., and Fine C.F. (1991), *Flexibility and performance: a literature critique and strategic framework*, Massachusetts Institute of Technology – Sloan School of Management, Boston.

Tolio T. (2009), *Design of flexible Production Systems – Methodologies and Tools*, Springer, Germany.

Ulrich, K. (1995), The role of product architecture in the manufacturing firm, *Research Policy*, No. 3, Vol. 24, pp. 419–440

Voss C., Johnson M., and Godsell J. (2016), Case Research, Karlsson, C. (Ed.), *Research Methods for Operations Management*, Taylor & Francis, New York.

Wahab M.I.M. and Osman M.F.S. (2013), *A fundamental flexibility measure: Machine flexibility*, paper presented at the 10th International Conference on Service Systems and Service Management, 17–19 July, Hong Kong.

Wallentowitz H. (2013), Fokus Batterie, Keichel M. and Schwedes M. (Ed.), *Das Elektroauto – Mobilität im Umbruch*, Springer, Wiesbaden.

Wiendahl H.-P. and Hernández R. (2002), Fabrikplanung im Blickpunkt. Herausforderung Wandlungsfähigkeit, *wt Werkstattstechnik*, No. 4, Vol. 92, pp. 133–138.

Wiendahl H.-P., ElMaraghy H.A., Nyhuis P., Zäh M.F., Wiendahl H.-H., Duffie N., and Brieke M. (2007), Changeable Manufacturing – Classification, Design and Operation, *CIRP Annals – Manufacturing Technology*, No. 2, Vol. 56, pp. 783–809.

Yin R.K. (2009), *Case study research: Design and methods*, Sage, California.

Zhong Y. (2015), *Flexibility assessment and management in supply chain: a new framework and applications*, available at https://tel.archives-ouvertes.fr/tel-01157143/document