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Comparison of Product Concepts in Terms of Modularity and Flexibility in the Automotive Industry

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Abstract: Flexibility is becoming increasingly important for companies to be able to react to the volatile environment. The automotive industry is particularly affected by this, due to the long time to market of vehicles and their increasing integration into cyber-physical systems. Automobile manufacturers must increase their responsiveness to product changes in product development and production. This paper compares two different vehicle product structures and presents an evaluation scheme for flexibility applied to the product structure with consideration of the corresponding production system.

Keywords: Modularisation, Co-Design, Uncertainty, Design Evaluation, Flexibility

1 Introduction

In today's business landscape companies must be flexible to be able to react to the volatile environment. With the integration of products into cyber-physical systems, they become more vulnerable to external influences. Products contain various technologies that undergo varying development cycles. Changes in customer and legal requirements are further change drivers. This results in increased product complexity and change frequency, which present new challenges for companies (Fricke and Schulz, 2005; Greschke et al., 2014). The development of products and product families with long development times and life cycles, such as in the automotive industry, is particularly affected.

The automotive industry is currently transitioning from the mature technology of combustion engine drive to electric drive. With regard to the electric drive, different technologies exist in parallel whose development and relevance for future vehicle concepts are uncertain. For instance, the axial flux machine is an alternative to previous types of electric motor. Additionally, there are various concepts for integrating the battery pack into the body in white, along with different cell concepts which vary in chemistry and design. These uncertainties do not only challenge the product development, but also the production system. Recent literature is discussing the limitations of the predominantly used line assembly concerning mixed-model production, adjustability to volume fluctuations and product changes in the automotive industry (Rachner et al., 2023; Huettemann et al., 2016). To overcome the limitations of the line assembly, a new type of production system was introduced which is referred to modular, reconfigurable or matrix-structured production system. Its main advantage with regard to flexibility is seen in the line-less structure free of a cycle time compared to the rigidly connected workstations of a line assembly subjected to a cycle time (Rachner et al., 2023).

This raises the question of the right degree of flexibility of a product under consideration of the corresponding production system. Therefore, this paper analyses the relation between the modular structure of the product and the production system in terms of flexibility and suggests an evaluation scheme. Chapter 2 provides a brief overview of measures for flexibility and presents two distinct examples of product structures from the automotive industry, which are compared in chapter 3 regarding flexibility. The paper concludes with a discussion of the concept comparison and the applied measures for modularity and flexibility.

2 Research background

In the context of product development, it is important that future changes for product family care are to be achieved with low effort (Martin and Ishii, 2002). On the one hand, the integration of change into the product (family) shall be of low effort and on the other hand its implementation into the production system. Therefore, the product and the production system must both provide flexibility. In the literature, many different definitions and types of flexibility can be found, especially in the field of manufacturing science. However, researchers have not agreed on a consistent definition of flexibility, its different types, and measures so far.

2.1 Measures for flexibility

The product’s flexibility is analysed and evaluated at different levels. Martin and Ishii (2002) evaluate product architectures at the component level regarding the effort in redesign to meet expected future changes. They introduced the generational variety index and the coupling index. The generational variety index depicts the redesign effort of a component as the share of the initial design costs and is determined by estimating future changes expected for the product lifetime and the respective scope of redesign (in terms of extent and costs). The coupling index reveals the likelihood of a component to cause changes at other components or to be impacted by changes of other components. Similar approaches are presented by Dan and Tseng (2007) and Weck and Suh (2006). Dan and Tseng (2007) defined the flexibility index which depicts the ratio of the intended change to the total change (including side effects due to change propagation). Weck and Suh (2006) introduced the change propagation index which classifies components as multiplier, carrier, absorber and constant according to their contribution to change propagation. It is derived via a binary Design Structure Matrix, which shows the influence of a component on others and the impact from others on the component in case of predicted changes. The difference of the amount of incoming and outgoing change impacts states the change propagation index. Weck and Suh (2006) further consider costs for redesign and necessary investments for the implementation of product changes into the production system.

Others evaluate product flexibility at the module level such as Stryker et al. (2010) who evaluate the flexibility of a product within the so-called vector modularity measure. The vector consists of four dimensions: degree of coupling, reusability (within the meaning of commonality), reconfigurability and extensibility. The four dimensions align with the definition of properties and characteristics of modularity according to Salvador (2007). However, the authors only see reconfigurability and extensibility as contributing to flexibility. Reconfigurability is expressed as combinability of modules within the product at four different levels of granularity. Extensibility is the ratio of possible future functions already considered in the development to implemented functions.

Uckun et al. (2014) propose an architecture-based approach to assess the flexibility of a product by evaluating its modularity, hierarchy, interfaces and sensitivity with the help of Design Structure Matrices. Modularity is measured in terms of physical and functional connections within and between modules. Hierarchical structuring is seen as an enabler for “selective evolution” (Uckun et al., 2014). Interfaces are distinguished in standard, flexible, adaptable, and nonstandard. In case of change, flexible interfaces allow redesign to a certain degree. Adaptable interfaces can be refitted via adapter pieces. Mathematical formulars are provided to calculate the characteristics and an overall measure for flexibility. However, it is unclear in what range the measure should lay.

In production science, many evaluations of flexibility are based on the six core characteristics of reconfigurability defined by Koren et al. (2018): scalability, convertibility, diagnosability, customisation, modularity and integrability. The six characteristics describe reconfigurability in terms of changes in structure and system components for adjusting capacity and functionality of the production system. For example, convertibility is defined as the ability to adjust the functionality of a system or a machine for the integration of product changes (Koren et al., 2018). Modularity, defined according to Salvador (2007), encompasses the other five characteristics of reconfigurability. Koren et al. (2018) refer to the clustering of production units into modules based on functional aspects for organizational decoupling, considering modularity as a separate characteristic.

Gumasta et al. (2011), Beauville dit Eynaud et al. (2022) and Jesus (2023) evaluate the flexibility of the production at the system and machine level by calculating one or more measures for each characteristic, whereby the last two mentioned neglect diagnosability. Only the measures for modularity and integrability are identical. An overview of the five measures is used for the comparison of the different production concepts. No further support is provided on the interpretation of the measures, although the best overall solution cannot be clearly identified in all cases. An approach to evaluate the flexibility at equipment level is provided by Berlec et al. (2013). Therefore, the equipment’s flexibility is assessed with regard to its universality, mobility, modularity, compatibility and economy, based on further sub-criteria depending on the type of equipment. Chehami et al. (2023) suggest an overall measure for flexibility consisting of the weighted sum of key performance indicators contributing to flexibility, such as presented above. Another approach, less objective than those mentioned above but easier to conduct, is presented by Aurich and Barbian (2004). Similar to the FMEA, the so-called Flexibility Mode and Effect Analysis evaluates process modules for their influence on different selected flexibility types (Aurich and Barbian, 2004). The evaluation scheme consists of the three categories weak, medium, and strong, without further specification.

Manufacturing science considers the flexibility of the product’s design as well (Sethi and Sethi, 1990; Kubota et al., 2022) and emphasizes the advantages of modular product design from the perspective of production (Kubota et al., 2022). Kubota et al. (2022) discuss the role of modularity in product design as well as in production and how they influence each other. According to them, further research is necessary to harmonize the modular structure of the product and the production system in the best possible way to achieve strategic goals (Kubota et al., 2022). This statement is in line with the numerous diverging and overlapping definitions and measures of flexibility provided in the literature. Flexibility as a strategic aspect enabled by modularity (Fricke and Schulz, 2005; Sanchez, 2004), is still difficult to assess and transfer into design guidelines.

2.2 Modular product concepts for vehicles

Last year, the automobile manufacturer Tesla presented a new vehicle concept whose product structure differs significantly from the conventional designs. The vehicle concept was developed with the aim of reducing production costs and throughput times as well as the space required for production (Tesla, 2023). In addition, the new vehicle concept should enable a significant increase in the degree of automation in assembly (Tesla, 2023). To this end, the principle of allowing the product to grow steadily during assembly and avoiding the joining of small components to significantly larger components, such as the body in white, is being pursued (Tesla, 2023). The new product and production concept is called unboxed. According to Tesla (2023), the unboxed concept reduces the space required for production and improves accessibility for assembly processes. The Japanese automobile manufacturer Toyota followed shortly afterwards with a similar concept (Dolan, 2023).

Figure 1 shows the assemblies of the final assembly of the unboxed concept compared to the assemblies of a conventional product structure for the final assembly. A conventional final assembly line typically involves over 100 assembly steps. Components in the form of sub-assemblies and further smaller components such as lights are fitted to the body in white according to the customer's order. To simplify the example, the assembly of various smaller components such as the rear lights, is neglected in this study as indicated in Figure 1. Apart from the breakdown of the final assembly modules, no further details of the production processes and system have been released by the automobile manufacturer Tesla. However, we know from currently produced products from Tesla that components are pre-assembled, rather than being fitted individually to the body in white.

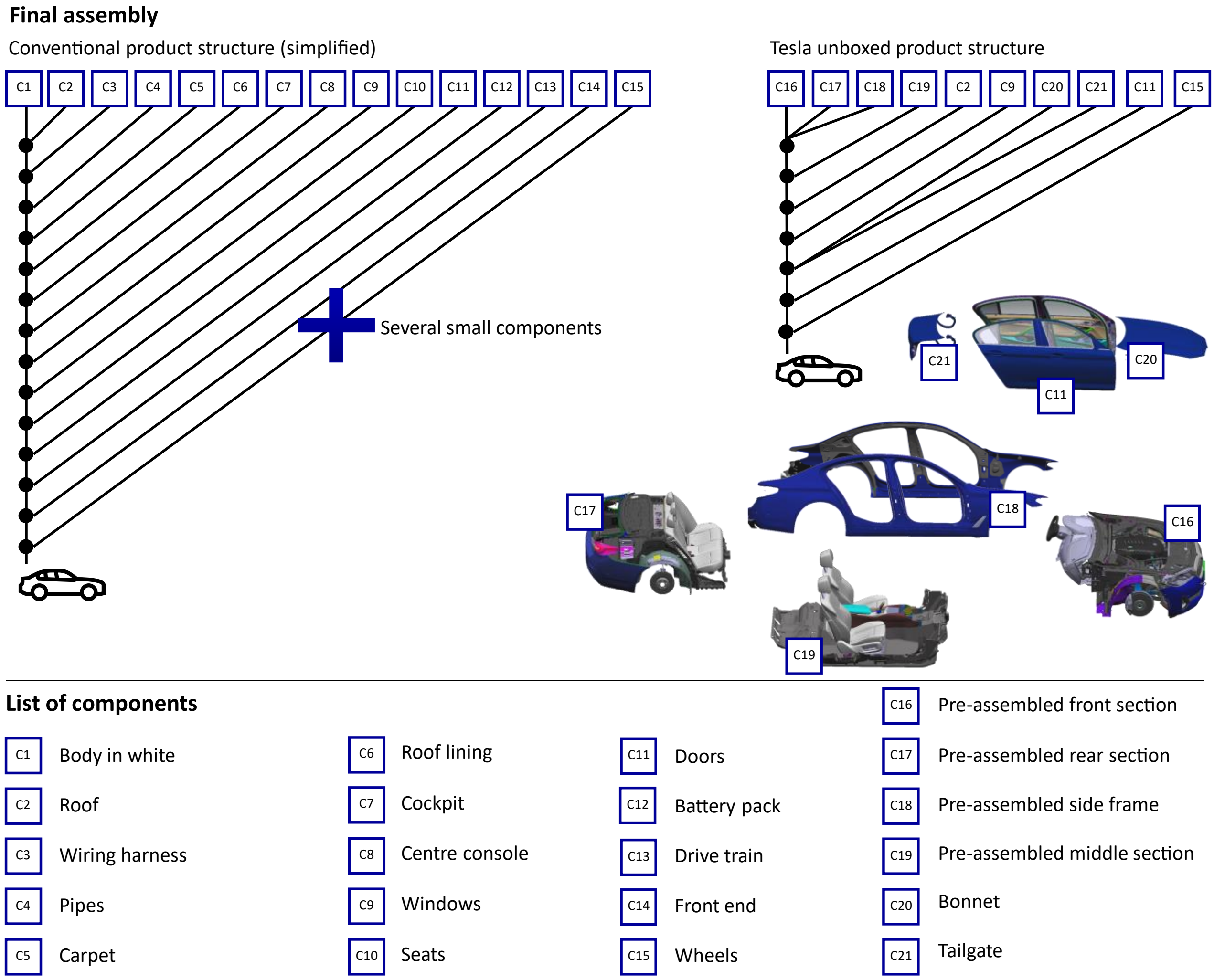

Figure 1. Comparison of the conventional (left) and unboxed product structure (right, according to Tesla (2023)) of a vehicle with regard to the final assembly

The introduction of the unboxed concept was not explained from a product development perspective. For this reason, we focus on the modular product structure from the perspective of production. The assemblies in Figure 1 represent the modular product structure of the final assembly. Given the volatile market environment with fluctuating demand, changes in requirements and rapid technology cycles, the question arises as to the advantages of the unboxed concept in terms of flexibility when considering the frequent changes for which Tesla is renowned.

3 Comparison of vehicle concepts in terms of modularity and flexibility

This chapter compares the unboxed concept from the automobile manufacturer Tesla with a conventional vehicle concept based on the G30 from BMW, with regard to their advantages in a volatile market environment.

Many of the key figures presented in chapter 2 are complex to determine and require information which is not available for the unboxed concept (as for the early phase of product development). Moreover, the key figures do not provide any information on the reasonable level of flexibility to achieve, which may result from the coordination of the modular structure of the product and the production system. They also fail to create transparency for optimising the analysed concepts in the future. In the following, the product structures of the two concepts are compared in terms of modularity and flexibility with regard to assembly.

The conventional concept was developed for the production in an assembly line. This is reflected in its product structure, which employs the body in white as a carrier for the numerous components to be assembled. Along the long process chain of a line assembly, the assembly steps are distributed as evenly as possible while maintaining the specified cycle time to achieve the desired production volume. For instance, the front section of the vehicle is assembled in sequential steps along a large part of the assembly line, with each component being added one after the other. The rear section of the vehicle can be installed concurrently with activities on the front section. From a final assembly point of view, the cockpit, centre console, doors, battery pack, powertrain and front end are modules that are decoupled and outsourced in pre-assemblies. In addition, components mounted on the underside of the vehicle were grouped into a module for the swivel conveyor section. The same applies to the allocation of the windows to the same section of the assembly line for the gluing process in order to save on additional gluing systems and to increase their utilisation.

For the sake of simplicity, we only consider the 14 sequential steps of the conventional concept’s final assembly, shown in Figure 1. In the conventional product structure of the final assembly, certain components are already combined into modules. However, there is still potential to combine further components with pre-assembled assemblies and thus into modules. The vehicle's mounting parts for the bonnet and tailgate, which are mounted on the vehicle, are examples of components discussed. These and other smaller components could already be pre-assembled on suitable carrier components, such as the rear lights on the tailgate. The module cockpit is in turn pre-assembled in sequential steps in an assembly line. The components of the module drive train are grouped into lower-level modules through several pre-assemblies, as illustrated in Figure 2 for the unboxed concept. The modules of the final assembly’s product structure are reflected in the production areas (see Figure 3), indicating the modules of the production system (consisting of workstations). In the event of product changes, additional or different assembly scopes can be integrated into the line assembly by shifting assembly steps across the assembly line. An increase in cycle time is not permitted. However, cycle time losses or even idle strokes are accepted. Due to cycle time and geometrical constraints, it is not possible to achieve a perfectly balanced distribution of assembly steps along an assembly line on which a wide variety of product variants and generations are manufactured. In addition, assembly scopes can be outsourced to pre-assembly or to suppliers. Product changes, which require less effort and no structural intervention in the production system, can be integrated during running production without downtime. Product changes that strongly influence the assembly sequence and require intervention in the (physically) fixed transfer system, are rarely implemented due to the high investment and production downtime involved.

From a final assembly perspective, the unboxed concept, which was designed for assembly, consists of the modules pre-assembled front and rear section, side frame (left/ right), middle section, bonnet, tailgate, front and rear door (left/ right) (Tesla, 2023), as well as modules for windows, roof, and wheels. Provided that modules such as doors, bonnet and tailgate are concurrently mounted to the vehicle as shown in Figure 1, the final assembly consists of seven sequential assembly steps.

For the unboxed concept, no further information is available on the product structure of the pre-assembly and production system. However, a breakdown of the Tesla Model Y (produced in Austin) does allow conclusions to be drawn about the module structure of the front section. Accordingly, for the unboxed concept, it can be assumed that the pre-assembly consists of a front section of the body in white, an aggregates carrier, a drive train front, a cockpit, and a front end which are assembled into the front section within 3 steps (see lower part of Figure 2). Some of the components consist of further pre-assemblies such as the drive train front whose product structure is shown in the upper half of Figure 2. The drive train consists of the pre-assembly/ module front axle carrier (M1), two sway bars (M2), the electric drive (M3) and further components which are summarised to the module drive train front (M4). The cockpit states a module (M5) itself, as it is assumed not to contain any pre-assemblies like the conventional concept.

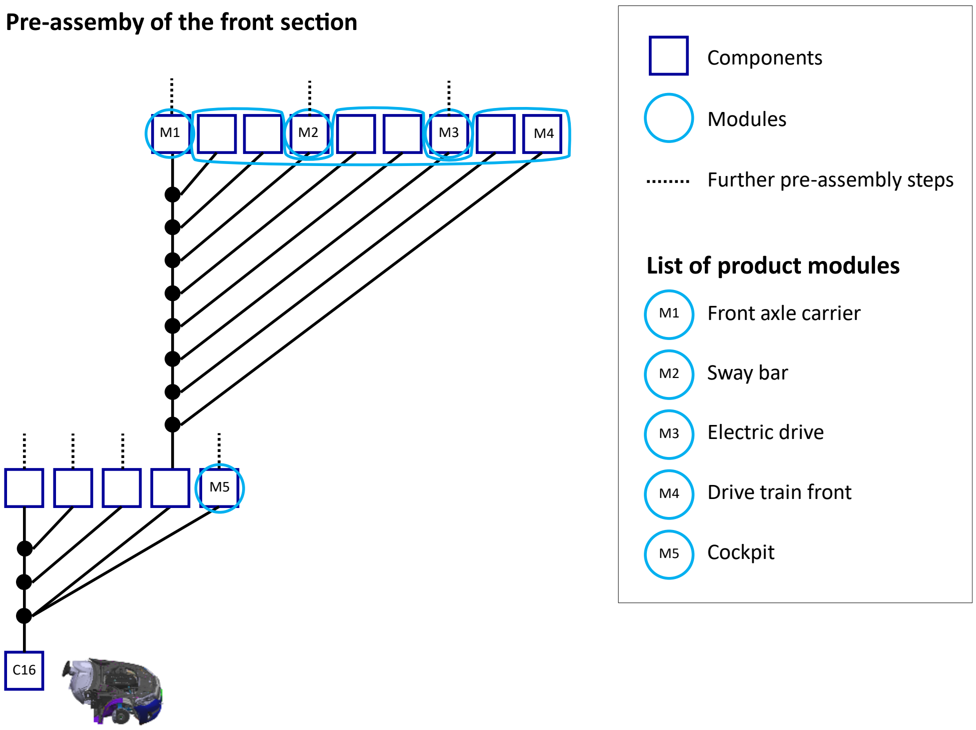

Figure 2. Product structure of the pre-assembled front section including modules

In conclusion, the main difference between the two concepts, within the scope examined, is the shift of the joining of the three sections of the body in white and the side frames from car body construction to final assembly. Consequently, many of the sequential steps for mounting single components onto the body in white can be moved to pre-assemblies comparing the conventional with the unboxed product structure, assumed that the two vehicle concepts consist of comparable components. These components either build additional pre-assemblies or are combined with conventional pre-assemblies. Compared to the conventional product structure, the unboxed product structure has significantly fewer sequential steps in the final assembly and contains a higher proportion of pre-assemblies (see Figure 3). Decoupling of the assembly process is achieved through the separation of pre-assemblies from the sequential assembly steps, such as the cockpit. However, the cockpit carrier is used as carrier component for other components being mounted sequentially onto it from the start of the assembly process until it is finally assembled on the vehicle. The separation of the body in white (the carrier component in the conventional concept's final assembly) into its pre-assemblies and their usage as carrier components allows to decouple larger production areas and to assemble concurrently. The unboxed product structure depicts a more decoupled product structure with fewer sequential assembly steps in a row, leading to a network or area-like production structure with shorter assembly lines.

A conceivable option would be a matrix production with workstations in parallel. Sequential assembly steps of a short assembly line can be combined into one workstation. Such a workstation may need to be duplicated within the production system, to achieve the desired production volume. A matrix production is characterized by a flexible transfer system, such as automated guided vehicles, and decoupled workstations (Huettemann et al., 2016). This allows for variations in the process sequence and process time (Huettemann et al., 2016). In addition, the layout without defined production lines makes it easier to integrate additional workstations or reallocate them to other modules of the production system. Allocating product changes to decoupled workstations facilitates their integration, as opposed to distributing them across an assembly line, which can affect upstream and downstream assembly steps. This is made possible by forming modules based on their structural coupling. In the case of redundant workstations, changes can be implemented without production downtime. To take advantage of the strategic benefits of a matrix production in terms of flexibility, the product must have a decoupled product structure consisting of many independent carrier components which serve as the basis for module formation from an assembly perspective. The decoupled modular structure of the product and the production system increase transparency and facilitate change implementation.

Comparing the two product structures in terms of flexibility, the unboxed concept contains less sequential restrictions and provides a higher degree of decoupling which can be mirrored in its production system. A product with a conventional product structure cannot fully benefit from the strategic advantages of a matrix production in terms of flexibility, due to its high number of sequential steps in relation to its number of pre-assemblies.

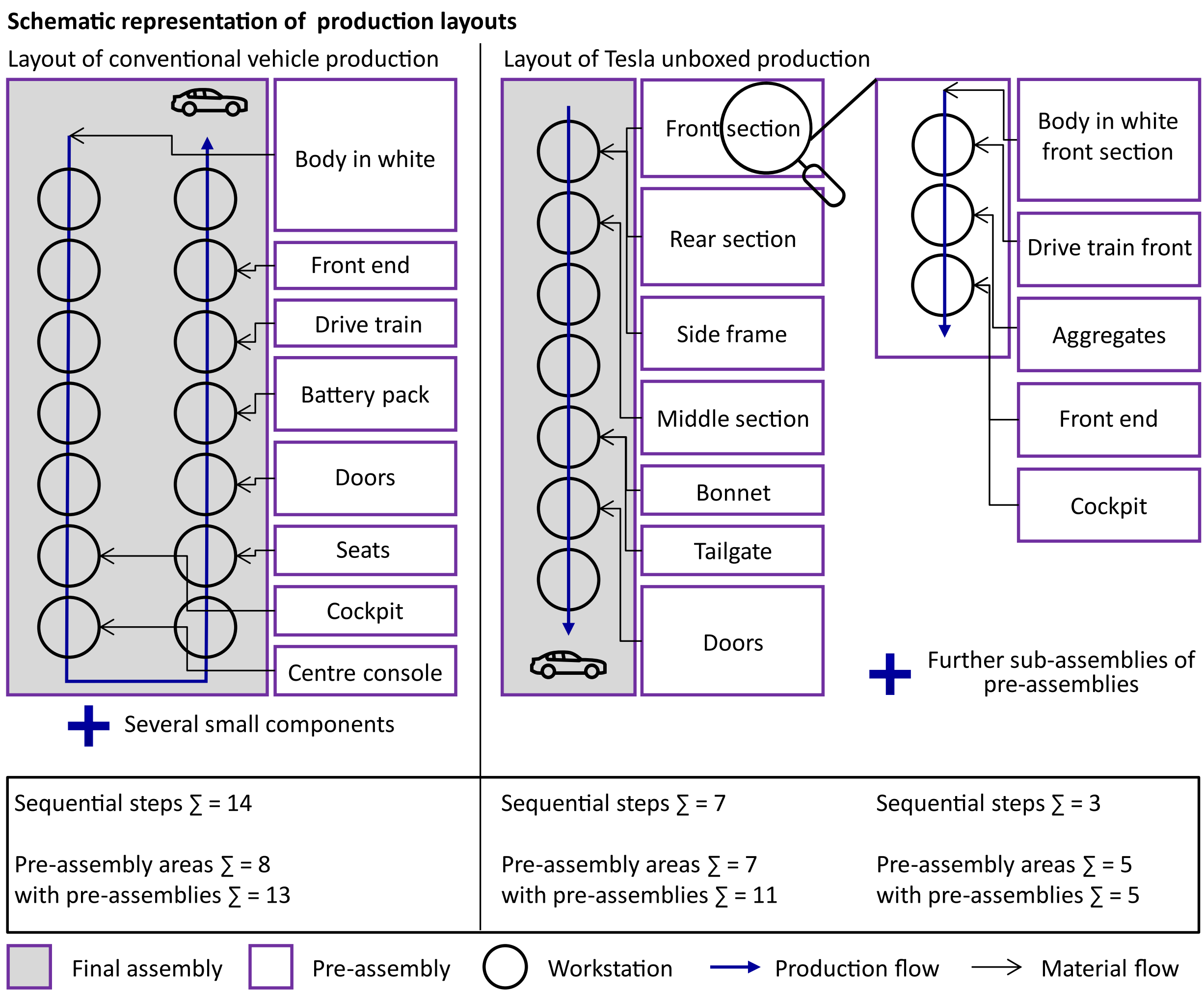

Figure 3. Comparison of the production system of the conventional and unboxed concept

4 Discussion

In contrast to the complex and time-consuming evaluation schemes from the literature presented in chapter 2, the applied measures used for the analysis in chapter 3 are easy to assess and compare. The number of sequential steps and the pre-assemblies to enable concurrent assembly are suitable indicators for the ease of change integration. These measures provide sufficient significance for evaluating the product structure in terms of modularity and flexibility. They align with the characteristics associated with modularity and flexibility in the literature. The required information can be obtained from the developed product structure itself.

Instead of evaluating the coupling of components or modules in terms of interface strength and thus likelihood of change propagation, this paper suggests evaluating the coupling in terms of assembly sequence and thus allocation to production unit. Concerning the integrability of product changes in the production system, the number of pre-assemblies of the final assembly, is a suitable indicator for the degree of decoupling in the concept phase and quickly to assess. In addition, the number of sequential steps derived from the product structure provide further insights about the structural coupling of modules and potential for improvement. To further analyse the product structure, the evaluation can continue at the pre-assembly and body construction levels, provided that the required information on the product structure is available. A high number of carrier components and decoupling points accompanied by a low number of sequential steps provide higher flexibility with regard to the implementation of product changes in the production system. In the concept phase, it is advisable to aim for a high number of pre-assemblies and thus modules for rough planning purposes. Furthermore, the component size with regard to its handling is a good indicator for its integration into or separation from a module. During the detailed planning stage, it is necessary to re-evaluate the number of modules, taking into account production performance aspects. This can be done with the aid of simulations. Unnecessary component handling in assembly can be reduced through the merging of modules, thereby increasing the performance, and finding the right balance between decoupling and performance.

The flexibility potential of the production system depends on its modular structure and can be best exploited when aligned with the modular product structure. For instance, creating a vehicle with a conventional product structure in a line-less assembly still has limitations in terms of flexibility due to its high proportion of sequential assembly steps. The unboxed concept's higher degree of decoupling allows to assemble a high number of modules in parallel and at different workstations. The implementation of common workstations permits the sharing of workstations across different modules, with each workstation being used as needed, based on the actual process time and customer orders. In addition, the modularity of the product and the production system enables the further development of the product module by module, such that the influence is solely on single production units. The module wise product modification facilitates the implementation of changes in product and production in terms of ease and speed, thereby increasing flexibility. This is contingent on an adjusted corporate structure.

The initial transition from the conventional production system to a matrix requires investments in a flexible conveyor system and the rearrangement of workstations. Flexible conveyor systems such as driverless transport systems are already used in modern production systems but are routed along a line and tied to a cycle time akin to conventional flow production. The product itself can be manufactured with common production processes. The modular structure of the unboxed concept provides greater accessibility for assembly, thereby enabling the automation of further process steps. The challenge lies in the intelligent control of the production system with regard to the production and the material flow. The material flow can be organised in a manner analogous to Just-in-Sequence or Just-in-Time, as it is currently with the ability to bypass individual workstations in case of errors. The field of machine learning provides promising solutions in terms of self-learning algorithms.

The transition from the conventional production system to the matrix system can be accomplished in a stepwise manner and serving as initial trial, beginning with the pre-assembly. However, the unboxed concept cannot be integrated into conventional assembly lines regarding the final assembly. Such a change in the product structure requires the implementation of a new production system, which offers the advantage of being installed with a minimum number of workstations and the ability to scale as demand grows.

Once the system has been implemented, it can be used to produce prototypes as alterations of series products. Product changes can be integrated into series cars for testing of the modifications in the form of new functions and design. This represents a significant enhancement in responsiveness with regard to the availability of prototypes for testing. Moreover, this facilitates the assessment of the impact and maturity of the integrated product changes on the product, as the behaviour of the series product is stable and well documented from previous tests. In addition, the integration of prototype production into series production provides the opportunity for early feedback on and validation of the production concept.

This study is limited to the perspective of production due to the available information. It may be beneficial to conduct further assessments on the flexibility of product concepts with regards to product development. Aspects related to product variety had to be neglected. The standardisation of key figures, which is typically done to improve comparability, was neither possible.

5 Conclusion

This paper provides a brief overview of measures for flexibility and presents two distinct examples of product structures from the automotive industry. The product structure of a conventional vehicle concept is compared with the so-called unboxed concept introduced by the automobile manufacturer Tesla in terms of modularity and flexibility.

For the evaluation of the product structure from the perspective of production, the degree of structural decoupling of modules is used as an indicator for modularity and flexibility of the product concept. The structural coupling was assessed by the number of pre-assemblies depicting decoupling points and the sequential assembly steps. A product with a conventional product structure is constrained by the process sequence and cycle time and thus less flexible, due to its lower degree of structural decoupling. The product structure of the unboxed concept by Tesla is better decoupled from the perspective of assembly. A higher proportion of modules represents pre-assemblies produced in parallel. The modular character of the product structure of the unboxed concept is reflected by the modular structure of the so-called line-less assembly or matrix production. This new type of automobile production is claimed to offer greater flexibility than a conventional line assembly. Nevertheless, it is essential to align the modular structure of the product with that of the production system in order to optimally exploit the flexibility potential.

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