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Mobile Assembly of Electric Vehicles: Decentralized, Low-Invest and Flexible

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***Abstract*—**The growing speed of innovation in related industries requires the automotive industry to adapt and increase release frequencies of new vehicle derivatives which implies a significant reduction of investments per vehicle and ramp-up times. Emerging markets in various parts of the world augment the currently dominating established main automotive markets. Local content requirements such as import tariffs on final products impede the accessibility of these micro markets, which is why in the future market exploitation will not be driven by pure sales activities anymore but rather by setting up local assembly units. The aim of this paper is to provide an overview of the concept of decentralized assembly and to discuss and critically assess some currently researched and crucial approaches in production technology. In order to determine the scope in which complementary mobile assembly can be profitable for manufacturers, a general cost model is set up and each cost driver is assessed with respect to varying levels of decentralization. One main result of the paper is that the presented approaches offer huge cost-saving potentials and are thus critical for future production strategies. Nevertheless, they still need to be further exploited in order for decentralized assembly to be profitable for companies. The optimal level of decentralization must, however, be specifically determined in each case and cannot be defined in general.

***Keywords*—**Automotive assembly, e-mobility, production technology, small series assembly.

I. Introduction

E-MOBILITY causes a disruptive change in the automotive industry. Due to the high degree of novelty of the applied technologies in e-mobility, development leaps are expected during the next few years that will change both automotive systems and production processes. In line with the growing importance of information and communication technology, innovation cycles are significantly reduced; time-to-market stays a determining competitive factor [1]. Companies introducing their products earlier onto the market than their competitors will more likely get a high and stable market share. This is achieved by exploiting learning curve effects, i.e., the effects of decreasing average and marginal costs with increasing production experience, economies of scale and increased willingness to pay of some customers – the early adopters – in the first stages of the product life cycle [2]. Accordingly, release frequencies – the frequencies of launching new vehicle derivatives – must adapt to the growing speed of innovation in related industries in order for automotive companies to stay competitive.

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This paper presents the concept of mobile assembly by explaining several crucial approaches in the field of production technology of e-mobility production such as self-driving chassis, smart logistics, tolerance compensation elements, 3D-printed fixture elements, augmented reality and the shift of long-sighted production planning towards a more flexible production control are presented.

In Chapter II, the most relevant trends and challenges of the market are explained and contrasted by the analysis of today's automotive production in Chapter III. Based on these facts, Chapter IV presents the decentralized and flexible mobile assembly along with approaches from the field of production engineering of e-mobility production as enablers for this new form of assembly. Finally, Chapter V concludes this paper by summarizing the most important elements and provides a direction for future research.

II. Trends and Challenges

Current trends and developments pose new and diverse challenges for the automotive industry. Concerning to the speed of innovations the automotive industry is trailed far behind other large industry branches such as the electronics industry. Comparing the product life cycles of the Volkswagen (VW) Golf to the iPhone reveals a significant difference – there have only been seven models of the Golf on the market in the last 42 years (see Fig. 1) while Apple launches a new iPhone model every year, resulting in an innovation speed which is six times as fast [3].

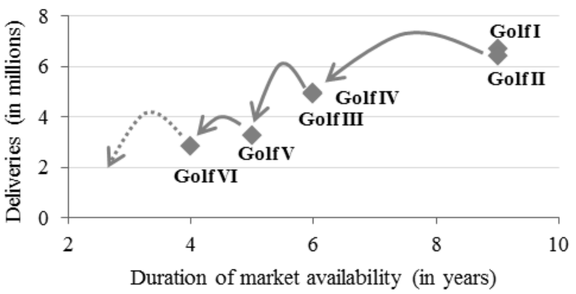

Fig. 1 Duration of market availability and number of deliveries of VW Golf [3]

Although the innovation cycles in automotive production have already decreased in the last decades, a further reduction is required to be able to fulfil the changing and increasingly individual customer needs, to stay competitive and to adapt the vehicles to the constant technical development [4]. The rising pressure to innovate is a phenomenon that has become increasingly crucial, as customer requirements have become more complex and divergent depending on the origin, the age and the personal interests. Besides, automotive producers have to approach further challenges beyond their core competences like the fast moving field of electronics [5]. Customers' requirements are not restricted to the car itself but comprise the newest infotainment, navigation systems and telematics services as well. However, life cycles in the information and communication industry are shorter compared to those of automobiles [5]. Ensuring a higher release frequency requires the minimization of ramp-up times and investment per vehicle.

The market situation has been changing rapidly and significantly during the last decades. It is expected that 66% of the world population will live in cities in 2050 – today, this proportion is 54% [6]. Additionally, the total world population increases: According to a prediction of the UN Department of Economics and Social Affairs (DESA), it will grow from current 7.4 billion up to 9.7 billion until 2050 and up to 11.2 billion until 2100 [7]. A consequence of these developments is the growing number of megacities, i.e., cities with at least 10 million inhabitants. While there were only ten megacities in 1900, there are 28 of them today. In 2030, the estimated number of megacities will amount to 41 [6]. Therefore, most markets will manifest by economic autonomous and urban metropolises in the future.

In consequence of economic growth, the number of potential markets for vehicles is increasing and the few existing large core markets are supplemented by globally distributed micro markets while at the same time the particular requirements in the markets are heterogeneous. The underlying reasons for this heterogeneity comprise local differences in wealth and thus the willingness to pay, in the demands concerning comfort, design and driving enjoyment of a vehicle or in the function the product is expected to fulfil. New and undeveloped markets establish and former irrelevant markets become increasingly important. For example, the Association of Southeast Asian Nations (ASEAN), which includes countries such as Indonesia, Malaysia and Singapore, has experienced a faster and more stable growth than the European Union since 2000. Real GDP growth was 5.1% in ASEAN states between 2000 and 2013 while it was 1.8% in the United States and 1.1% in Germany [8]. Income growth has been strong as well during the last decades with an average yearly rate of more than 5%. About 67 million households in the ASEAN states belong to the consuming class, i.e., they have an annual income of at least 7,500 USD (in PPP) [7]. This is why ASEAN states are expected to have new car sales of 4.6 million by 2020 which are more than the 4.4 million new car sales that are predicted for Russia. The same development will take place in the Mideast (5.8 million) compared to Brazil (5.2 million) [9].

Currently, the automotive industry tries to face customers' needs for individuality by mass customization offering apparently individualized vehicles in nearly unlimited configuration possibilities. By means of extensive analyses of user behaviors and preferences, actually individualized vehicles can be offered according to the specific requirements of the respective micro markets thus enhancing customer value. Local content requirements impede the accessibility of these micro markets. Hence, import tariffs, for example, are circumvented by disassembling the vehicles produced in mass factories and transporting them in single components to the destination country, in which they are reassembled again in CKD-factories [10]. Due to the logistics effort, the high additional costs and the resulting inefficiency of this approach, it is necessary to think about a more economical and efficient way to avoid high import tariffs.

Ongoing trends reveal that the automotive market has never been as heterogeneous and geographically diverse as it is today. Core markets such as Europe, United States and Japan have been volatile. The financial crisis in the US demonstrated how severely OEMs are affected by an economic downturn of an established market. In order to meet the market challenges all players in the automotive industry have to recognize the need for geographic diversification to balance production and risks and to actually meet heterogeneous market demands.

Consequently, market exploitation can no longer be driven by pure sales activities but rather by setting up local assembly. If vehicle assembly takes place locally in each micro market, manufactured quantities per plant are smaller implying the necessity for an optimized production of small series.

III. Automotive Production Today

Currently, automobile production is designed for innovation cycles of several years and is characterized by structural rigidity, high investments and centralized mass production capacities. In conventional mass production a high number of vehicles is produced in each production facility. Audi for example manufactured 566,646 vehicles in its production site in Ingolstadt, Germany in 2015 [11]. The essential amount of value added in the automotive production takes place in few large mass factories in the partly stagnating core markets North America, China and Europe. The investment costs for such assembly lines are between 55 and 220 million USD [12]. The production systems designed for efficiently producing enormous quantities of vehicles are only limitedly able to manufacture individualized vehicles. Existing small series assembly for premium and sports cars is based on large-scale technologies distributing high investments among few vehicles. For instance, Rolls Royce Motor Cars sold 3,785 vehicles in 2015 with long assembly times and high manual assembly content [13]. These facts imply that current production systems are not dimensioned for the prevailing developments. A potential solution is provided by mobile assembly, which combines central component production with decentralized vehicle assembly in globally distributed micro markets with the aim of enabling a cost-efficient and flexible production - both in terms of number of units and vehicle models - of customized vehicles close to the target market.

Today, OEMs' production structures are highly optimized and cost-effective and at first sight, supplementary local assemblies seem to imply additional costs. This complementary production structure of mobile assembly, however, offers some cost-saving measures in addition to a closer customer contact, faster delivery times as well as shorter, thus more ecofriendly transport routes. Nevertheless, merely transferring the structures and processes of today's large series assembly to a decentralized production does not yield the desired benefits but assembly has to be entirely adapted, new processes and production engineering approaches have to be developed in order for mobile assembly units to be a reasonable complement. Economic research must be conducted to determine if there is a second potential minimum in the aggregated cost curve of OEMs for the case of decentralized assembly with central component production (see Fig. 2). If such a point exists, the optimal level of centralization must be defined.

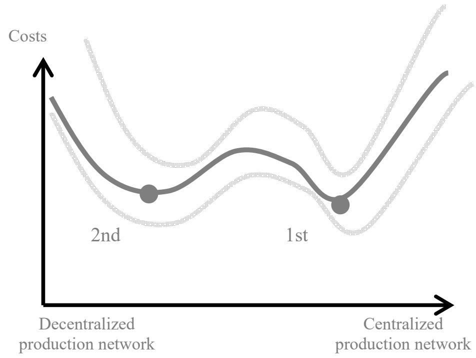

Fig. 2 Aggregated cost curve

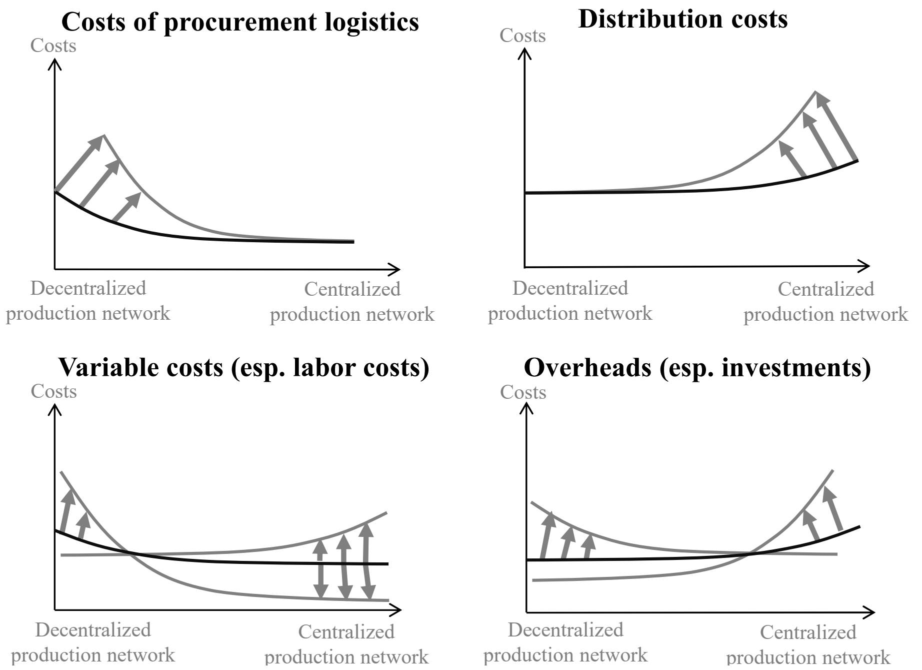

Fig. 3 Comparison of costs for two different production structures

In order to determine if and when the complementary decentralized mobile assembly can be profitable, each cost driver needs to be separately analyzed in detail. Important costs in this context are amongst others distribution costs, costs of procurement logistics, variable costs and overheads, which again consist of various cost drivers and are depicted in Fig. 3. These costs vary depending on the level of centralization. On the one hand, outbound logistics are, for example, simplified by local production sites as the finished products are already in the destination market implying a shorter delivery distance to the customers and the avoidance of import tariffs. On the other hand, procurement logistics complicates when many small assembly sites in different markets have to be supplied and the components must be brought to many different instead of only some locations. With regard to variable costs and overheads, the decentralization of the assembly might have cost-cutting as well as cost-increasing effects and it is still unclear which effects overweigh. In a small series assembly, the level of automation is relatively low resulting in a higher proportion of employees and consequently increasing labor costs. At the same time, overheads decrease compared to a large series assembly with highly automatized and expensive equipment, which is product-specific and thus must be exchanged if new derivatives are introduced. Additionally, costs for setting up several low-invest local production units must be compared to the costs of building few large production sites. The question remains how exactly a decentralized production will be conceived: Will assembly take place in each megacity or metropolis or will there just be one or two assembly units per country? This exemplary analysis reveals the need for a detailed approach to determine if the costs of a decentral production network can be kept down so that the aggregated cost curve has another minimum. In any case, new approaches and innovative technologies are required to enable an economical small series assembly.

Electric vehicles are especially suited for mobile assembly due to a significantly higher variance in their adaptable vehicle architecture that enables alternative vehicle concepts and different configurations. The lower technical complexity of the interfaces, the reduced number of components as well as the lower scope of added value in the assembly allow a multi-variant small series production of vehicles [14].

PEM at RWTH Aachen University develops solutions in the field of production engineering to implement a decentralized and flexible production network for electric vehicles, in which customer-specific vehicles are produced in small series.

IV. Approaches Based On Production Technology In The E-Mobility Production

One approach to enable an economical decentralized e-mobility production yields at the substitution of classic assembly lines like conveyors and suspension tracks by the own abilities of the electric chassis. The overall idea is to break the rigid and linear assembly structures and build assembly segments which can be designed more task- and product-specifically as illustrated in Fig. 4. Different products can thus pass in different paths through the assembly system depending on the exact derivative and specifications of the vehicle, which is not possible in usual assembly lines.

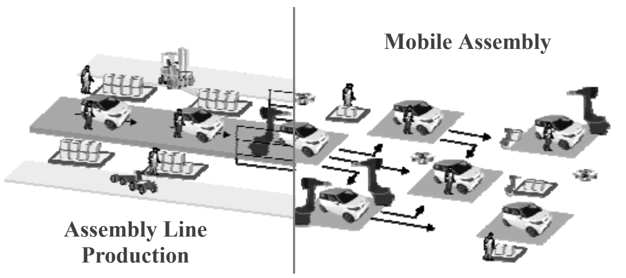

Fig. 4 Assembly line production vs. mobile assembly

Six approaches in the field of production engineering of electric vehicles are presented in the following sections: self-driving chassis, smart logistics, tolerance compensation elements, 3D-printed fixture elements, augmented reality and a shift of production planning towards production control.

A. Self-driving Chassis

One enabler for efficient small series assembly systems in the electric vehicle production is the reduction of structural investments in expensive conveyor technology for vehicle transport by self-driving chassis, which navigate themselves through the assembly system. The aim of self-driving chassis is to shift the function ‘transport through assembly’ from the assembly system to the product itself. Thus, it becomes necessary to relocate the integration of the powertrain to the beginning of the assembly and to establish an independent navigation through the final assembly by setting the individual routes of the vehicles in a central instance. Self-driving chassis can undertake the task of their own transport as soon as they are equipped with all required drive components such as energy storage, electro motor, inverter, actuator and sensor technology plus servomotors, e.g. at the steering gear [15]. In order to achieve this, fundamental adaptations to the product and process are required as well as the configuration and implementation of the appropriate communication technology, e.g. an interface to the superior assembly control. Merging the assembly object with the assembly transport system decreases investments as well as operating and labour costs. The configuration of the assembly steps is more vehicle-specific and it is possible to continuously adjust the structure and sequence to be more flexible in terms of variants. Furthermore, the chassis can take individual routes and hence skip assembly stations they do not need to visit or postpone them to later assembly steps. Consequently, the assembly system will be self-scaling and flexible and resequencing of chassis after certain steps in the assembly process will be much easier.

B. Smart Logistics

Flexible assembly concepts, which are based on a dynamic and continuous resequencing of the assembly objects, require a different logistic supply than conventional assembly [16]. To cope with the available flexibility, so-called ‘smart logistics’ need a smart control unit and new principles of material supply. The conventional central control units are not able to react in an appropriate time to changed conditions, which is why decentral smart control units are part of the products. The products will be able to communicate which each other and coordinate further actions depending on available capacity of the assembly stations and the specific assembly precedence graph [17]. Due to the unique and unpredictable assembly history of every product, the provision of components has to be executed on short term. Until now, the components are provided by well-known principles like carset picking, Kanban, just-in-time or just-in-sequence which usually require long-term planning. For mobile assembly, a more flexible concept is needed, realized for example by enabling communication between the product and the supplies, so that a merely product-driven provision is possible [18]. Today’s logistic supply in the automobile production is designed for flow assembly and hence very rigid due to clearly defined areas for material supply, tact control and distinct traffic routes. For this reason, adaptions for a flexible assembly concept have to be made. Smart logistics are freed from this rigidity by using flexibly movable areas for material supply and dynamic as well as self-optimizing traffic routes, which are used by autonomous trollies instead of tugger trains and conventional trollies. In addition, 3D logistics allows the usage of the third dimension for internal logistics processes and is realized, for example, by drones.

C. Tolerance Compensation Elements

While in large series assembly, the alignment is realized through investment-intensive and highly automatized robots and measurement technology with a focus on avoiding tolerances, mobile assembly has no such high investment budget due to economic reasons and therefore has to handle larger tolerances, which leads to higher assembly times. Those highly iterative alignment processes are expensive and time-consuming as they need several repetitions of the alignment and thus have to be replaced by a more flexible and less costly approach for small series in mobile assembly facilities. A more suited approach is the substitution of conventional alignment processes by individually produced tolerance compensation elements, whose construction must be included in the product development process. The production process consists of four steps (see Fig. 5). First, the components are three-dimensionally measured usually by means of an optic measurement system in order to create a virtual subtraction of an actually measured picture of an assembly group, e.g. of a door and the door flange, from an ideal engineering drawing. The subtraction of the digital pictures provides information on real variances. The second step is the comparison of the measured information and the CAD files to deduce the tolerance variances. On this basis, tolerance compensation elements can exactly be calculated and individually produced, for example by means of additive processes. This procedure allows a precise insertion of the compensation elements into the particular tolerance chain. Thereby, it is possible to compensate tolerances easily and individually in a big spectrum to save costly and time-consuming alignment processes and to uncouple the alignment from the assembly.

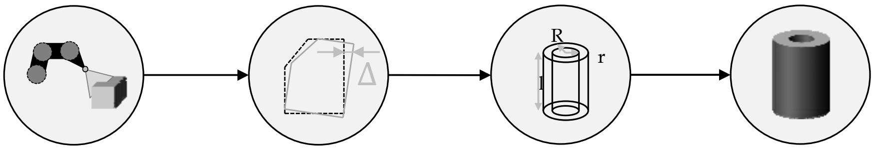

Fig. 5 Depiction of the manufacturing process of a tolerance compensation element

D. 3D-Printed Fixture Elements

For the transformation of today’s assembly systems towards an improved responsiveness with respect to changing products it is necessary to enable fixture constructions for the mobile assembly to provide appliances and implements faster, more flexibly and less costly compared to fixtures employed in large series assemblies [19]. The missing synchronization of product- and appliances-data currently prevents an immediate integration of product changes, whereby considerable delays in the innovation process arise. A technology to equip small series assemblies of electric vehicles with the required fixtures are modular construction systems with standardized interfaces for different use cases, an example of which is shown in Fig. 6. Such systems can flexibly be adapted to product changes. While the replacement of the component-specific appliances can be realized with little effort, the development and manufacturing can be very costly and time-consuming [20]. With the help of 3D-printing the processing time can significantly be reduced [21]. Even though this approach is already partly applied in the automotive production, the actual potential lies in the complete automation of the development and production process of the fixture elements and is not exploited yet. A rule-based deduction of appliance drawings from CAD engineering drawings of the assembly object enables the generation of data usable by 3D-printers to finally produce fixture elements fully automatized by a continuous data stream.

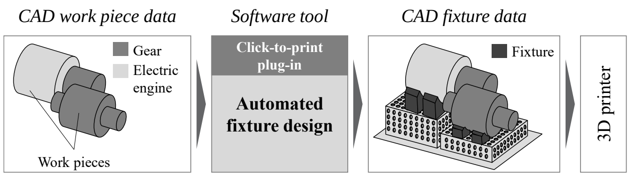

Fig. 6 Result of the automated design of fixture elements

E. Support by Augmented Reality

Another new approach to enable decentralized small series assembly are augmented reality solutions. Augmented reality is an innovative technology that can support the assembly staff, for example by displaying information related to operational tasks into the visual field of the wearer of the glasses. These glasses are already utilized for instance in the logistics sector where they help to pick the correct articles in the correct sequence from the shelves. Nevertheless, the state of the art is more an *assisted* reality as usual glasses applications do currently not overlay the real scene but add a screen into the upper area of the visual field of the worker. Thus, the aim is to develop a real augmented reality solution displaying information into the real world. In the automotive production smart-glasses contain high potentials. They enable for example an individual and flexible assembly as printed instructions at the workstation are substituted by digital overlays that can easily and directly be edited by the process engineers and that can also be differentiated from product to product without much effort. Compared to instructions in unhandy folders, smart glasses are hands-free and do not impair workers’ mobility. Still, augmented reality solutions also bear some challenges such as high energy requirements. Including the technology into the glasses causes them to gain weight and hence, they are sensed by the wearer more than normal glasses are. Such technical problems still need to be solved but still, augmented reality solutions provide a high potential to indeed simplify the assembly processes for the workers and to support their activities. Especially for local assembly units such augmented reality solutions help to quickly train new employees and thus be able to produce small series flexibly and efficiently.

F. Production Control

The mobile assembly requires a change of the scope of production planning and production control. Production planning is conducted in the medium run and comprises production program, material requirements and production process planning. The production control currently releases and supervises the orders based on this planning whilst steering the entire production flow, also in case of short term disruptions [22]. The idea of mobile assembly in contrast is breaking free from existing deterministic planning approaches and predetermined build sequences. It aims for a high frequency assembly planning situation in which production planning and control are increasingly coalescing. This in turn is inevitable for decentralized nonlinear assembly and implies a significant reduction of planning efforts. However, changing the assembly structure, layout and processes in the short term can only be efficiently achieved by digital innovations making the system capable of dynamic line balancing and resequencing. This comprises smart linkages between equipment and vehicles as well as the ability of self-optimizing systems through the use of real-time and response data [23]. Digital shadows of the products as well as the production facilities enable a complete digital picture of the entire production at real-time. If the transition to less production planning can successfully be implemented, there might be no planning offices needed at each assembly site, which in turn would be an important cost-cutting aspect whilst offering increased flexibility.

V. Conclusion

The presented approaches from the field of production engineering as well as further approaches have to be researched more deeply to be able to ensure an economical mobile assembly of customized electric vehicles in globally distributed micro markets. Besides these technologies the establishment of fundamentally different added value and logistics structures is necessary to realize assembly facilities close to the market. To keep the increasing logistics expenses within an economical useful scope, the configuration of the flow of material and information within the outlined production network still poses a central challenge due to the market-specific product design and requires further research. Comparable to conventional CKD-factories in markets with high local content requirements, the implementation of mobile assembly capacities must be possible with little investment and overheads.

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