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Advances in Automotive Production Technology – Theory and Application

Stuttgart Conference on Automotive Production (SCAP2020)

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Editorial

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Stuttgart Conference on Automotive Production: Advances in Automotive Production Technology – Theory and Application

Mobility as well as the production of its means currently undergoes the vastest changes since Henry Ford introduced the moving assembly line for its Model T in 1908. Today, the very industry that produces interconnected automobiles sees itself constantly confronted with questions regarding interconnected and smart production systems, with the necessity of an increasingly rapid incorporation of various enabling technologies, and issues of data management & interoperability. It does not come as a surprise then that there is a promising intersection of product and production technologies, at which the intelligent product becomes part of the production process already. Vice versa, an intelligent product has all the technical requirements to inform production over the course of its entire life-cycle whilst simultaneously benefiting from the data produced by every single comparable vehicle; i.e. the “fleet-intelligence” informs both product and production.

Now, the practical questions that arise from the above stated hypotheses are obviously manifold. And, more importantly, not to be answered or solved by any single researcher, developer, or disruptive inventor. What they actually require is the exchange of solution approaches and expert knowledge as well as a practical take on collaboratively answering some of the more pressing issues.

The successor to last year’s “Stuttgarter Tagung zur Zukunft der Automobilproduktion”[1], namely, the *Stuttgart Conference on Automotive Production (SCAP2020)* set out to be a forum that would not only allow for the exchange of concepts and ideas but also for very specific answers within precisely

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[1] Stuttgart Congress on the Future of Automobile Production.

defined solution spaces. The framework in which all contributions of the conference would operate was defined by the questions mentioned at the beginning and given the following headline: *Advances in Automotive Production Technology – Theory and Application.*

The SCAP2020, organized by ARENA2036 in collaboration with Fraunhofer IPA, University of Stuttgart, Startup Autobahn powered by Plug and Play and IEEE TEMS, has proven to be a stimulating forum for researches from the sciences, the industry, and startups allowing every participant to learn about important current trends, gain insights regarding the overall research landscape, and to find ways in which a transfer from theoretical approaches to practical applications becomes feasible.

Every single contribution up for discussion was peer-reviewed by either members of the scientific committee comprised of 19 international experts or by individual domain experts for specific subject matters. Accordingly, and in order to ensure the scientific quality of the conference in general and of this volume in particular, the organizing committee of the SCAP2020 was in the position to choose the contributions to the conference from a far larger number of submissions.[2]

The contributions in this volume are arranged thematically in four parts, allowing the readers to choose their fields of interest from a broad range of automotive production technologies. Part A focusses on *Novel Approaches for Efficient Production and Assembly Planning*, Part B on *Smart Production Systems and Data Services*, Part C discusses *Advances in Manufacturing Processes and Materials*, and Part D presents *New Concepts for Autonomous, Collaborative Intralogistics.*

Now, we would also like to thank everyone involved in planning and running the conference, as well as all the contributors to and attendees of the conference – especially Dr. Jörg Burzer, Rainer Brehm, Prof. Dr. Thomas Bauernhansl, and Prof. Dr. Soumaya Yacout for their inspiring and insightful keynotes.

Finally, we would like to invite you to stay in touch with ARENA2036, to stay tuned for SCAP2022, and to enjoy the following papers.

Stuttgart
11/30/2020

Philipp Weißgraeber
Frieder Heieck
Clemens Ackermann

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[2] This book includes contributions submitted directly by the respective authors. The editors cannot assume responsibility for any inaccuracies, comments, and opinions.

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Part A New Approaches for Efficient Production and Assembly Planning

Agile Hybrid Assembly Systems: Bridging the Gap Between Line and Matrix Configurations

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Abstract. The ongoing transition towards electro-mobility requires an increased reactivity and reconfigurability in automotive assembly. However, the traditional line assembly, which is characterized by rigid cycle times and linear product flow, has already been pushed to its flexibility limits. Drivers are the increase of product changes, variants and derivatives within assembly lines. To further increase reactivity and reconfigurability, matrix structured assembly configurations are a possible solution. Several studies highlight the theoretical advantages, but it has not been applied and validated in industrial use-cases, due to the high transformational gap between line and matrix configurations. In contrast, segment-wise line-less structures show a high potential for this.

A use-case oriented approach improves reactivity and reconfigurability by implementing an agile hybrid assembly system that combines the advantages of line and matrix structured (also referred to as line-less) assembly systems and offers a lower investment threshold. Three fields of action are presented: The first consists of flexible planning and control software modules. Within the planning phase, an automated scenario analysis is performed for optimization by applying simulations. During the production phase, the simulated model is re-used for the operation of a dynamical multi-agent manufacturing execution system with online scheduling algorithms. The second field of action deals with reconfigurable infrastructures, which comprises short-term dispatching intralogistics and a flexible layout, facilitated by AGV transport routes and reconfigurable self-adaptive workstations. The third field of action comprises a system model that is an underlying fully integrated digital twin. Control interfaces integrate the infrastructure into the manufacturing execution system to enable rapid system changes.

The presented hybrid system contributes to the design of future assembly systems by showing which aspects of line and matrix configuration can be combined to have a beneficial impact on a broad spectrum of production scenarios. By considering all relevant fields of action in a holistic way and by analyzing a hybrid configuration, the arising challenges for producing companies are addressed in a practical and functional manner.

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1 Introduction

The transition towards electro-mobility has a profound impact on the development of Original Equipment Manufacturers (OEMs) and the entire value chain of the automotive industry [1, 2]. German, American and Japanese OEMs are announcing over 80 new electric models for 2019/20 alone [3]. The parallel production of conventional, hybrid and purely electrically powered vehicles confronts OEMs with major challenges and the growing product variance on integrated assembly lines is leading to far-reaching efficiency losses [4]. In addition to the high variety of products OEMs are facing, product lifecycles are being shortened, making even more reconfigurations of the production line necessary [5]. As today's globalized society opens new markets for manufacturers, competition is increasing accordingly. A customizable product and efficient, cost saving manufacturing remains the best way to gain an edge over competitors and increase product value [6].

The stated trends are particularly evident for automotive assembly. Assembly has a significant impact on the value chain, accounting for 50% of production time and up to 20% of total costs [7, 8]. Since the final assembly will remain a core competence of OEMs in the future [9], novel strategies for the successful transformation of the industrial value-chain towards electro-mobility must take the design of assembly systems into account.

Currently, assembly systems for automotive production are designed for stable market environments and only a few changes at a time [10]. They are limited by fixed transfer systems (e.g. roll conveyors) and only very few buffers. To further increase reactivity and reconfigurability and thus meet future requirements, matrix structured assembly configurations (also referred to as line-less) present a promising solution [11, 12].

The basis for matrix structured assembly systems is the removal of the restrictions imposed by fixed transfer systems, enabling movements between different assembly stations [5]. However, due to the high transformation gap between line and matrix structured assembly systems, industrial applications have not yet reached a practical level [11]. Further, the full potential of matrix structured assembly systems can only be explored when the product´s precedence graphs contain a certain level of flexibility.

Accordingly it can be assumed, that an assembly system should contain both, elements from matrix and line configurations, creating a hybrid form. Thus, this paper presents a use case based design approach for hybrid assembly systems, which incorporate the advantages of both matrix and line structured assembly systems.

2 Theoretical Background

Matrix-structured assembly systems have been well studied and explored over the past years. However, there exists no uniform terminology and classification for the description of matrix-structured assembly systems yet. Thus, the following explanations are intended to highlight the most important characteristics in a cross-section manner.

The aim of matrix-structured assembly systems is to design a more flexible assembly system in comparison to line assembly, while maintaining the same efficiency and profitability [12]. Flexibility is achieved by decoupled assembly stations and assembly stations arranged in a matrix structure. This allows for a dynamical adjustment of assembly process sequences within the restrictions of the assembly precedence graph as required during operation. [13, 14]. The assembly sequence as well as the route of each job is not proactively planned and determined, but defined according to the availability of resources and other situational circumstances such as the availability of workers, station efficiency, transport times or even malfunctions at stations [13, 14]. The absence of a higher-level cycle time eliminates the need for assembly scheduling or line balancing [12, 15]. Sequence flexible assembly thus enables the realization of flow assembly with different cycle times or cycle-independent assembly stations, as well as the production of highly individualized products within the same assembly system [12]. A requirement for the operational feasibility is the existence of a real-time control system, e.g. based on multi-agent system [16].

Further advantages of the matrix structured assembly system are the scalability and reconfigurability. Scalability can be achieved by duplicating bottleneck resources at station or equipment level. Reconfigurability is realized by the modular design of the assembly stations as well as associated resources [17, 18]. When reaching a situational and near-real time adaptation of the assembly system, the term “agile assembly system” is used. The planning process is characterized by a comparatively later as well as smaller reduction in systemic degrees of freedom compared to line assembly [19].

All outlined aspects show that the tasks of planning and controlling matrix structured assembly systems are increasingly merging [20]. In case of strong restrictions such as limited flexibility of the precedence graph or space availability, it is sensible to transfer only specific manufacturing segments into a matrix structure. This will reduce complexity as well as the transformation gap and costs. For these reasons, a framework for agile hybrid assembly systems is presented below, which addresses the segment-by-segment break-up of line structures both in terms of the relevant fields of action and the selection of potential production segments.

3 A Framework for Agile Hybrid Assembly Systems

The framework for an agile hybrid assembly system combines the advantages of line and matrix assembly systems. This way, the high efficiency and output of line configured assembly systems are expanded by the adaptability and flexibility of matrix structured system. Therefore, elements and principles from both configurations are considered for the design of an agile assembly system (see Fig. 1).

A boundary condition for efficiency is a production scenario that clearly shows potential caveats regarding key performance indicators e.g. adherence to due dates, utilization and reconfiguration cost. Such a production scenario could be the described parallel production of vehicles with various powertrain systems, which would result in an increasing complexity of tasks and planning efforts. In addition to the efficiency the profitability can be maintained. Operational costs, as one measure of the profitability, correlates with the system’s efficiency. In addition, profitability includes investment costs, which need to be taken into account for a transition towards a matrix system. Thus, possible circumstances to maintain profitability are savings in operational costs, due to a higher system’s efficiency in production scenario demanding for a flexible system.

One key enabler of a hybrid assembly system is the one directional flow used in line production. To dissolve bottlenecks, multifunctional assembly stations (i.e. stations capable of performing two or more assembly processes) can be duplicated und operated in parallel, a concept taken out of matrix structured assembly systems. Based on a simulation-based analysis of the required level of agility, it is determined which assembly stations should be duplicated, since highly efficient production segments can remain in the line configuration.

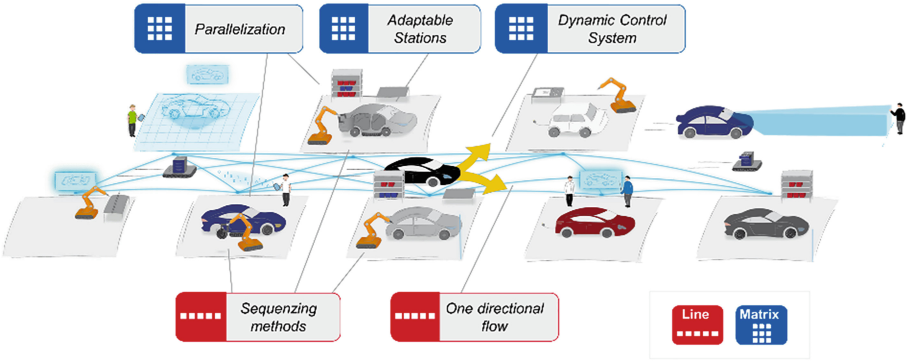

Fig. 1. Benefits of matrix and line configuration combined in hybrid assembly

To easily dissolve bottlenecks and allow for high utilization, stations must be highly adaptable. This includes the capability of stations to process multiple products and their variants. The utilization of the described flexibility requires the implementation of a control system. Various control architectures exist. A fully decentralized, autonomous system without a central control unit would be one implementation of a heterarchical architecture. Another approach would be a hierarchical control architecture, which is chosen when a set of tasks is required to be centralized. For an agile hybrid assembly system such a set of tasks demands for a hierarchical control architecture. The tasks are described in the following. The control system is responsible for the assignment of products to a specific work station. This is based on the product requirements and the work station abilities regarding the assembly operations. Also, it is responsible for the sequencing of assembly operations at the chosen work station. For these decisions, the control system may consider different factors such as the transport time, the redundancy of equipment at a work station or possible breakdowns at work stations. Since unforeseen changes on the shop floor can occur at any time, the control system needs to dynamically and frequently reassess decisions.

The framework for agile hybrid assembly systems adopts scheduling approaches for mix-model lines as they represented a validated method for optimizing the sequencing of orders. Since transport times are gaining considerable significance in matrix-structured assembly the scheduling approaches must be enhanced.

Operating a hybrid assembly system with maximum efficiency requires multiple components. These components can be grouped into three fields of action (see Fig. 2).

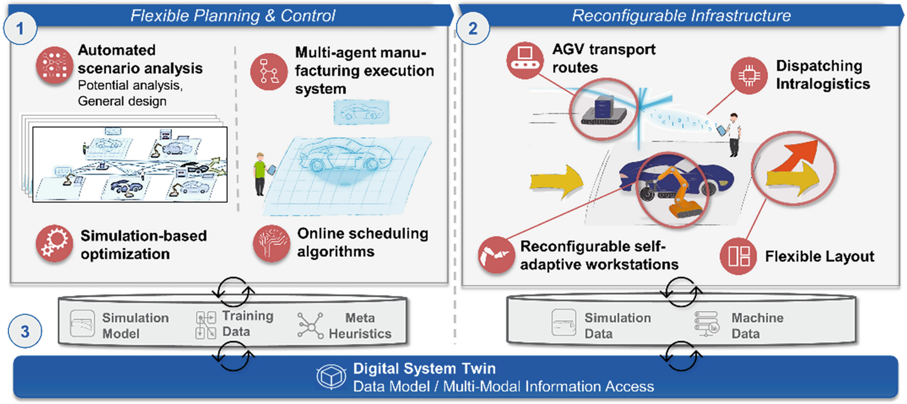

Fig. 2. System architecture and required technologies for an agile hybrid assembly system.

Flexible Planning and Control includes the before mentioned control system, also called the multi-agent manufacturing execution system, that coordinates every movement in the hybrid assembly system. The control system uses an online scheduling algorithm to assign each product its next process and the station that will carry out this process, planning an individual route for each job. For the planning phase of the hybrid assembly system, an automated scenario analysis is included. Its goal is the optimization of the production system by applying discrete event simulations (DES). Once production begins, the scenario analysis can be used to further improve production, analyzing data that was not available in the planning phase.

Reconfigurable Infrastructure enables the dynamic adjustment of production capacities. Autonomously reconfigurable workstations can adjust their capability profiles to handle an increasing and changing number of different processes. This makes a short-term dispatching intralogistics system crucial. The intralogistics system adapts to the flexible production layout and utilizes automated guided vehicles (AGVs) to ensure that all workstations receive necessary components and equipment for assembly. Although other transport vehicles can be used, AGVs are used as a representative vehicle form in this context. One feature of the system is the dynamic calculation of the AGV transport routes, reacting to sudden changes in production, like prioritization of certain jobs and breakdowns. Since the workstations are autonomously reconfigurable and AGVs can easily change routes, the infrastructure can be arranged in a flexible layout. This allows improvements if possible enhancements are uncovered during the simulation-based optimization process.

The underlying fully integrated **Digital System Twin** builds the connection between the first two fields of action as a structured and hierarchical data model. For the first field of action, the digital twin provides the data for training the online scheduling algorithms as well as the data for the simulation runs, done by the scenario analysis. To generate this information, the digital twin retrieves machine data from the reconfigurable infrastructure, e.g. movement information from the AGVs or processing times from the work stations. To solve optimization problems during the scenario analysis, metaheuristics are made available to the control system described in the first field of action.

4 Use Case Development

For the implementation of the fields of action and their components described in the previous chapter, use cases are defined. In theory, a use case is a description of actions that a system can perform with the participation of actors. An actor can be any entity that interacts with a system: a user, another system, but also the physical environment of the system itself [21–23]. Thus, an actor can activate a use case of the system. This use case can then activate applications within the system or request further information from other actors. In this way, use cases enable the attainment of a defined goal for the respective actors by describing the functions of a system and the benefits for the actors involved [22].

In the context of this paper, examples of relevant actors are infrastructure, automated scenario analysis, a dynamic multi-agent manufacturing execution system, shop floor employees, orders and resources. Within the production structures, actors can, for example, have the option to evaluate the potential of a section-wise parallelization or initiate the corresponding restructuring. The use case oriented approach guarantees the practical feasibility and reduces the transformational gap of the agile hybrid assembly system. The use cases themselves are planned in brownfield and are thus aligned with the restrictions of existing production environments. They aim to solve the production challenges addressed by the components of each field of action (see Fig. 3).

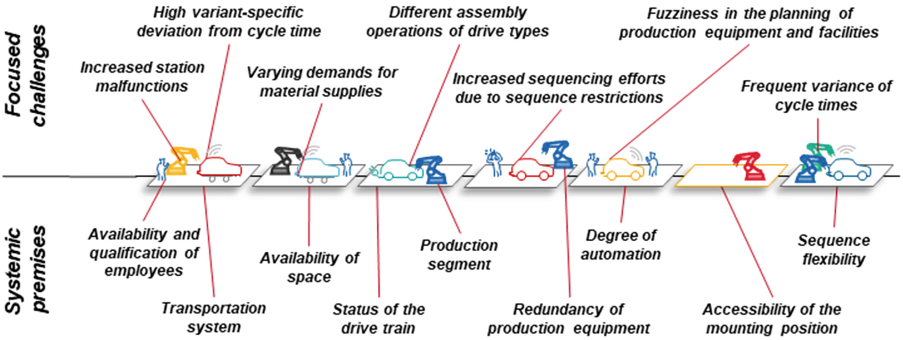

Fig. 3. Focused challenges and systemic premises for the use case development

A multi-stage procedure is applied for the collection and evaluation of the use cases. First, the three fields of action and each of their components are evaluated in an interdisciplinary project team regarding their possible integration into the current assembly environment. For this purpose, current structural improvement potentials of the assembly system, as well as assembly sections with restrictive and planning-intensive requirements are examined. The resulting integration concepts can then be consolidated in a list with specialist planners and evaluated using a qualitative criteria-based assessment of their potential. Selected integration concepts are then transferred into a detailed, standardized description, which include the basic functionalities, the systemic premises, the interrelationships of the systems and actors as well as description models for resources, processes and products. Those descriptions reflect the preliminary use cases and include alternative system configurations.

The preliminary use cases will then be transferred into a simulation model to further quantify their benefits. If a sufficient added value is proven, the relevant preliminary use cases need to be detailed with regard to their technological embedding and interaction in the existing system, e.g. the connection of the resources to the control system and concrete decision algorithms for decision making. The further development of the use cases is based on a hybrid planning strategy. This means that the development steps are divided into increments, which are further detailed either in a plan-driven way or developed in an agile way. By doing so, a late reduction of the degrees of freedom of the assembly system is guaranteed. This leads to a shorter development time by parallelizing work steps and also enables late modifications with little effort.

The necessary technological development requires cross-functional competencies and a close collaboration with the OEM companies. Parallel to this, the integration concept for the later system reconfiguration needs to be elaborated. This ensures that the necessary infrastructure and employee's competence are available in time for start of operation and that negative effects on the existing production system are minimized. By introducing use cases step-by-step the new components, e.g. the control system, can be tested and improved. Gaining experience with the concept will allow OEMs to apply the concept of matrix structured assembly on a bigger scale, integrating larger parts of the plant into the matrix, ultimately leading from hybrid manufacturing to a fully matrix configured assembly system, if reasonable. However, this is not always the ultimate goal. Some parts of production will always function best in line configuration, making hybrid assembly the most efficient manufacturing system in certain cases.

5 Conclusion

The presented hybrid system contributes to the design of future assembly systems by showing how aspects of line and matrix configurations can be combined to have a beneficial impact on a broad spectrum of production scenarios. By considering the relevant fields of action, i.e. flexible planning and control, reconfigurable infrastructure and digital system twin, in a holistic way and by analyzing a hybrid configuration, the arising challenges for producing companies are addressed in a practical and functional manner.

In addition to the presented fields of action an approach for the use-case development as a method for a practical implementation of an agile hybrid assembly system including the focused challenges and systemic premises was proposed. Further evaluation potentials would be the analysis of implemented use-cases regarding key performance indicators to achieve design guidelines for future implementations.

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Economic Feasibility of Highly Adaptable Production Systems

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Abstract. An increasingly uncertain market environment, high product variety and shortened product life cycles lead to an increased demand for adaptable production systems. Due to higher initial investment costs, it becomes more difficult to assess the profitability of such production systems with conventional methods, since the advantages of adaptable production systems are not considered sufficiently. This article presents an approach allowing to determine the economic feasibility of highly adaptable production systems which are repeatedly undergoing reconfiguration processes to adapt to products, processes and technologies that are unknown during planning and launch. In contrast to others, this approach considers a preferably high level of adaptability enabling the production system to change extensively and quickly. To test the method a scenario from the publicly funded project Fluid Production is used.

1 Introduction and Motivation

An increasingly uncertain market environment, high product variety and shortened product life cycles lead to an increased demand for adaptable production systems. In highly adaptable production systems, production resources are no longer used exclusively for one product family or production process, but instead are reconfigured repeatedly adapting to products, processes and technologies that are unknown during planning and launch. Due to higher initial investment costs, it becomes more difficult to assess the profitability of such production systems with conventional methods, since the advantages of adaptable production systems are not considered sufficiently.

2 State of the Art

To evaluate long-term investment projects dynamic investment calculation methods such as the internal rate of return (IRR) and the net present value (NPV) are frequently used in the industry [1]. In contrast to static methods these approaches consider the time value of money by taking into account the time payments are made. In addition, the life-cycle costing (LCC) and total cost of ownership (TCO) make it possible to consider costs and revenues over all life phases of an investment. Unfortunately, the application of these presented methods lacks the possibility to consider the flexibility and adaptability of production systems [1].

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Previous research to determine and evaluate the economic efficiency of adaptable production systems focuses on determining the optimal reconfiguration potential [cf. 2–7]. This approach assumes that the principle of diminishing marginal utility also applies to the ability to change, hence cost and benefit are not linearly related [5]. The procedure is not suitable for highly adaptable production systems, since maximizing reconfigurability is a fundamental component of this production concept. It is considered necessary to operate sustainably in a highly volatile and uncertain production environment. The close involvement of humans as well as the dynamic and needs-based configuration are intended to reduce the cost of versatility in production [8].

Life-cycle-oriented assessments based on the VDMA34160 [9], which include not only procurement costs but also operating and disposal costs, are presented by Schweiger and Pachow-Frauenhofer [10, 11]. The resources of highly adaptable production systems are composed of individual modules that are solution-neutral and not linked to a specific product in order to minimize pre-determinations and complexity costs. Additionally, the individual modules and their respective composition is changed continuously which leads to difficulties calculating the system's service life, since each module has its own useful life. Therefore, neither the product life cycle nor the service life of the system can be used as a basis for cost considerations [12].

The uncertainty of future developments represents another challenge during the evaluation of adaptable production systems. Möller [4] applies the approach of the real option theory known from financial mathematics to the problem of determining the economic feasibility of reconfigurable production systems under uncertainty. This enables the time-dependent consideration of uncertainty, but due to the calculation effort only a few parameters can be considered. Since highly adaptable production systems intend to improve the ability to act in a particularly volatile market environment, many different parameters must be analyzed.

In summary, it can be stated that the determination of the optimal reconfiguration potential is not feasible for highly adaptable production systems, since the planning framework is too uncertain and the necessary adaptability depends strongly on the respective operating phases. Furthermore, the requirements for the assessment of a variable evaluation period and the consideration of short-term and dynamic changes of resources in production have so far hardly been taken into account. Ultimately, an appropriate approach needs to be developed to allow the monetary measurement over a variable observation period and consider uncertainty in the production environment.

3 Approach

To periodically allocate occurring costs during the use of a configuration the model shown in Fig. 1 was developed. The observation period can be freely selected. The incurring costs are determined based on a component-wise evaluation of residual values at the end of each period. The occurrence of an adaption leads to a reduction of the residual value if components of the system are no longer required. This procedure was chosen because within highly adaptable production system it is very likely that most components can be reused, thus minimizing the number of obsolete components. As an outcome of the economic evaluation and foundation for an investment decision the NPV was chosen. It is determined in six steps.

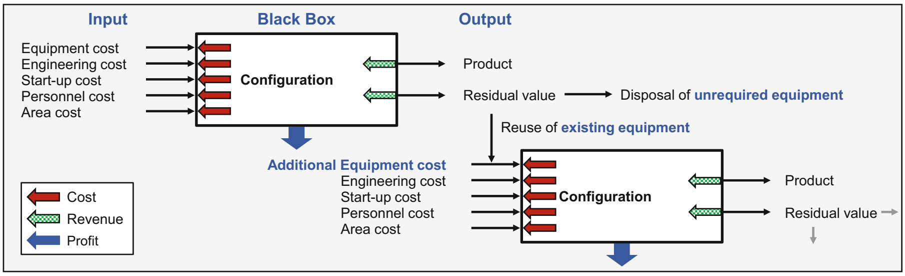

Fig. 1. Description model for highly adaptable production systems

In the first step, an analysis of possible production scenarios as well as the definition of general production conditions must be executed. The goal of the analysis is to determine key data like the annual quantity of units or product variants that are expected within the observation period. To set up a scenario funnel and to be able to consider possible future developments, worst- and best-case scenarios must be determined in addition to the forecast scenario [13, 14]. The production conditions include general production data like the shift model, the working days per year or the payment rate of workers.

The subject of the second step is the planning of the production system. This includes capacity planning by determining the production resources, such as type and number of machines and workstations, the linking in-between and the number of employees required for the production system in each period. The planning is based on the scenarios developed before, the required process technology and the assembly sequence.

In the next step the reconfiguration potential of the production system is determined according to Heger [2], allowing to estimate the share of components of a production system that can be adapted to new products, processes or technologies regarding certain conditions such as robot payload or dimensions of the assembly cell. However, Heger's method was reduced to essential aspects to evaluate the resources of a production system. The value of a plant object, such as a production resource or an entire production system, results from the sum of the individual normalized and weighted reconfiguration potential values of the system components of the object under consideration.

The fourth step involves the periodic compilation of costs arising in each period. This is done according to the LCC method presented within the VDMA 36160 guideline using the description model presented above. The costs of a period A_t consist of acquisition costs EK_t, operating costs BK_t and liquidation costs VK_t (see Eq. 1).

$$A_t = EK_t + BK_t + VK_t \tag{1}$$

The acquisition costs EK_t include investment costs for machinery equipment and tools as well as engineering and start-up costs. The operation costs BK_t comprise for example worker, area and energy costs. The liquidation costs VK_t consist of the disposal costs, the residual value of the production resources and other possible liquidation costs. Depending on the availability of data as well as the analyzed object and the degree of abstraction, the scope of considered costs can be adjusted as required. In the case of an adaption between two consecutive periods according to Stähr [6], the residual value RW_t results from the sum of the products of the reconfiguration potential values WP_y of the plant objects y and their present value $BW_{y,t}$ at the end of the corresponding period (see Eq. 2). If no adaption takes place between the individual periods, the residual value of the production resources RW_t is the sum of the book values of all plant objects used at the end of the period under consideration.

$$RW_t = \sum_{y=1}^{z} WP_y * BW_{y,t} \tag{2}$$

In the fifth step, the NPV of the production system is calculated based on the costs occurring in each period. It results from the sum of all incoming and outgoing payments per period within the observation period, discounted to the time of consideration.

In the last step, the results of the evaluation method are to be checked for accuracy and stability by means of a local sensitivity analysis [15]. By examining the dependence of the planning variants on changes in the production environment or on assumptions made initially, the resulting investment decision can be secured.

4 Example of Application

The application of the developed method is demonstrated by comparing a fluid manufacturing system (FLMS) with a designated manufacturing line (DML) using an exemplary product and quantity scenario. FLMS can be specified as highly adaptable production systems characterized by the ability to adapt and change dynamically to cope with challenges from increasingly volatile markets.

The comparison is based on a simple demo product. The product is composed of a housing with cover, a printed circuit board (PCB) and a battery holder which is mounted in the housing. While the mounting of the PCB and the battery holder are automated, the remaining processes are carried out at a manual workstation. These steps include inserting the batteries into the holder, connecting the wire to the PCB, flashing the software, adjusting the integrated potentiometer and final testing and mounting the housing with the customer label attached. It is assumed that the product will be available in three variants within a period of ten years. For product variant A all components are fixed by screws in the housing. A second product variant B is launched replacing parts of the screwing process with a bonding process and with a faster flashing of the software to achieve shorter cycle times and cheaper process costs for high quantities. Later, enabled by a technological innovation, variant C is launched including a friction welding process to further enhance the mounting and an automatic adjustment of the integrated potentiometer. However, the production of previous variants must be continued for a certain time. The assumed scenario (see Fig. 3) results from the four periods of the economic cycle (expansion, boom, recession, depression) and other expected fluctuations. As general conditions for the production in Germany 17 shifts per week with 7 working hours each shift and 272 working days per year were assumed. The respective batch numbers to be produced were set to be constant at 3000 units for product variant A, 1000 units for variant B and 2500 units for variant C.

An automatic assembly cell in the form of the highly adaptable CESA3R system [16] as well as the modular manual working station Active-Assist of Bosch Rexroth and a flexible linking with intermediate buffers are used in the FLMS. The modular concept of the CESA3R system, consisting of mechatronic objects with standardized hard- and software interfaces, allows the removal, replacement or supplementation of individual processes or technologies in the assembly cell or of whole assembly cells in the production system. Only the characteristics of the base cell, like the dimensions or the robot payload limit the reconfiguration potential and the productivity of the CESA3R system. For operation and setup of these systems, a continuous adaption of qualification requirements is necessary [17]. The concept allows a simple and accelerated start-up, e.g. in the form of a software-assisted safety assessment concept [18], which requires no additional specialists. A gradual increase in output is achieved by the parallel linking of cells. Thereby the assembly is carried out on supplementary cells in the same steps.

For the DML an automatic station and two or three manual workstations (depending on the product variant) were planned. The assembly takes place in a sequential process with a serial linking by a belt driven transfer system. The product specific process equipment and the sequential assembly allow a high productivity resulting from minimal cycle and setup times as well as a simple operation by auxiliary stuff. However, the production of new variants of an existing product or new products requires complex reconfiguration or even new construction of mechanic and electric components as well as software. In addition, changes to individual stations or the assembly line require extensive re-commissioning and process approval by specialists. An increase in output beyond the maximal capacity can only be achieved by a second assembly line.

The assumed investment and operating costs, cycle and setup times are compared in Fig. 2. The capacity planning is based on the assumption that a new configuration of the production is always necessary when either a new product variant is launched or the maximum possible capacity utilization of the current configuration is exceeded.

Configuration		Investment cost			Operating cost		Cycle time [s]			Setup time [min]		
		Equipment [€]	Engineering [€]	Start-up [€]	Personnel [€/P*a]	Area [€/m²*a]	Product			Product		
							A	B	C	A	B	C
FLMS	CESA^{3}R Screwing	100.000 €	21.385 €	▨	96.300 €	540 €	96	▨	▨	30	▨	▨
	CESA^{3}R Screwing + Bonding	120.000 €					96	76	▨	30	60	▨
	CESA^{3}R Screwing + Friction welding	135.000 €					96	▨	59	30	▨	90
	Manual Workplace	25.000 €	▨			291 €	83	78	68	0	0	0
DML	Screwing	225.000 €	30.662 €	10.621 €	70.600 €	1.328 €	48	▨	▨	30	▨	▨
	Screwing + Bonding	260.000 €					48	31	▨	30	60	▨
	Screwing + Friction welding	275.000 €					48	▨	29	30	▨	60

Fig. 2. Investment- and operating cost & cycle and setup time for DML and FLMS

Using the evaluation approach by Heger [2] the reconfiguration potential of the DML was rated with 30%. Due to reduced product commitment the FLMS configuration is highly adaptable but product specific requirements like the fixing equipment are limiting the reconfiguration potential at 90%.

Figure 3 shows the total costs of both production concepts and the quantity of the three product variants produced in each period of the example scenario. The initially lower costs of the FLMS result from the significantly smaller scaling steps per module. Combined with the faster start-up time this increases the degree of utilization of the FLMS for small piece numbers. On the other hand, at high production numbers many modules must be purchased and operated because of the required capacity. This reduces the economic efficiency of the FLMS with increasing quantities and explains its higher cost in the seventh period compared to the DML. The high costs of the DML in the third period result from an extraordinary depreciation that is incurred in this period because of the change of technology by the introduction of the friction welding process at the transition from the third to the fourth period. The FLMS can reuse most of the existing components which leads to reduced acquisition costs. Whereas the DML reaches its full potential in the seventh period due to optimal utilization it lacks the ability to adapt to the decrease in quantity in period eight. The FLMS concept can handle the changes in a more sufficient way and enables the production to operate sustainable even when the number of produced units is declining.

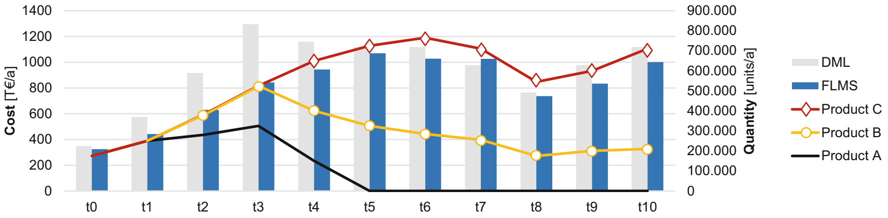

Fig. 3. Periodic cost analysis and accumulated quantity for DMS and FLMS

According to the periodic costs of this exemplary scenario, FLMS may be a more suitable alternative than DML. The accumulated NPV difference regarding an internal rate on return of 9% is 1.075.473 €. The difference in economic sustainability mainly results from the ability of FLMS to react more cost-efficient to fluctuations in quantity or the introduction of new products and technologies.

In the sensitivity analysis the reconfiguration potential value as well as the planning and start-up times were varied exemplarily, and a more intense development of the extreme scenarios was analyzed. It could be shown that the stability of the output variable is guaranteed in relation to the considered input variables. Nevertheless, the variation resulted in changes, which prove the influence of the selected input variables.

5 Discussion and Evaluation

The presented method allows to compare the economic feasibility of FLMS and DML. Due to the reconfiguration potential value determined according to Heger and the reconfiguration costs calculated therefrom according to Stähr, the adaption capability has a direct influence on the overall evaluation result. The developed description model allows the application of the LCC method for each individual period by describing it as a closed operating state with cost of acquisition, operation and liquidation. As a result, it is possible to consider the short-term and dynamic combination of resources in production systems and to analyze the profitability in an uncertain production environment over a variable observation period. Depending on requirements, the method can also be used to develop several scenarios with deviating forecasts, which can then be examined with the sensitivity analysis for their stability regarding varied input parameters. The determined NPVs can be compared in a results matrix to describe the situation under uncertainty. Depending on the risk tolerance of the management a suitable option can be chosen [19].

The application of the method to the exemplary product and quantity scenario resulted in the following findings for the comparison of FLMS and DML. The fast start-up time and the possibility of scaling in small steps increase the efficiency of the FLMS compared to the DML for low volumes significantly. This makes it possible to reduce the required capacities resulting in a reduction of the necessary acquisition costs. Even in the case of a technology or a product change, the individual acquisition costs are significantly lower for the FMLS than for the DML. On the other hand, the low scaling effect reduces the cost-effectiveness of FLMS at high volumes.

6 Summary and Outlook

The presented method allows to compare DML and FLMS during a selected observation period using the determined NPVs. The consideration of uncertainty in the production environment within the method is based on three scenarios determined in a scenario analysis (forecast, best- and worst-case) and a sensitivity analysis. Implementing methods for uncertainty evaluation like the real option theory, could lead to a more specific consideration of the aspect of uncertainty in the investment decision. But due to the complexity of the decision, the NPVs should not be the only valuated dimension of the investment decision. It is advisable to consider other factors that have a direct or indirect influence on the result. Possible factors are quality, working conditions or environmental impact.

The FLMS creates new degrees of freedom in the planning and operation of production. The so far only discrete adaption becomes a steady adaption and the solution space for possible adaptations is considerably larger due to short-term and dynamic combination of resources in production systems. Previously strategic decisions may become operational decisions. However, the additional degrees of freedom also go hand in hand with a much greater complexity of production. Digital planning tools could, for example, help to control the degrees of freedom and efficiently use the possibilities of FLMS.

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