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Deficits and Solutions in the Development of Modular Factory Systems

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***Abstract*—**As a reaction to current challenges in factory planning, many companies think about introducing factory standards to lower planning times and decrease planning costs. If these factory standards are set-up with a high level of modularity, they are defined as modular factory systems. This paper deals with the main current problems in the application of modular factory systems in practice and presents a solution approach with its basic models. The methodology is based on methods from factory planning but also uses the tools of other disciplines like product development or technology management to deal with the high complexity, which the development of modular factory systems implies. The four basic models that such a methodology has to contain are introduced and pointed out.

***Keywords*—**Factory planning, modular factory systems, factory standards, cost-benefit analysis.

I. Introduction

PRODUCING companies are facing an increasing complexity and higher dynamics in their business activities with a huge number of internal and external influencing factors [1]-[3]. These trends are due to the ongoing globalization that leads to several other developments such as a shortage of resources and shorter economic cycles. Results are rapid technology changes, challenging customer requirements and an increasing individualization of demands. Consequently, companies have to deal with shorter product life cycles, higher innovation pressure, a higher product diversity and fluctuating sales figures [4], [5].

In addition, the increasing cost pressure in globalized markets is a huge challenge for producing companies. The shortening of product life cycles leads to a higher frequency of factory planning projects and to a higher number of projects that have to be conducted simultaneously in interdisciplinary planning teams with ever-shorter project durations and lower budgets. In terms of their organizational structures, factory planning projects show a high heterogeneity with regards to the size and the composition of the mainly interdisciplinary planning teams and the involved other planning participants [6]. The mentioned challenges lead to big deficits concerning the target achievement of factory planning projects: Although most projects achieve the performance targets of the factory, cost and time targets are only rarely met [7]. An increasing cost pressure, shorter product life cycles and interdisciplinary planning teams will make the achievement of the main project targets even more difficult in the future.

Target of modern factory planning approaches hence must be the reduction of planning efforts to enable shorter project duration and a faster production ramp-up. In this paper, a solution approach will be presented that uses methods from different scientific disciplines. Main target is the development of modular factory systems that increase the efficiency during the planning process by using standardized factory elements with defined interfaces. The biggest potential of modular factory structures can be identified in the planning phase of a new production facility, in which they provide a big opportunity to reduce planning efforts, planning times and complexity [8].

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II. State of the Art of Modular Factory Systems

In this paper, modular factory systems are defined as systems that consist of a large amount of factory modules of different characteristics and functions. By combining these modules in different ways, an enormous number of overall factory variants can be generated.

The definition of factory modules can hereby consider different levels within a factory. For example, for a bigger company a whole production line can be a factory module that is then combined with other modules, such as the material provision concept or the building services. Whereas for smaller companies a single working place could be a factory module or even in more detail a single tool or material trolley.

In the literature, there are approaches that deal with the concept of modular factory structures. One similarity of all approaches is that they try to decouple the different factory elements by generating independent modules that have standardized interfaces. In the following, some selected approaches will be presented.

One of the first approaches regarding the modularization of the factory was developed by Wildemann with his concept of production segmentation. In this approach, the modularity comes from product-oriented organizational units, which contain several steps within the production chain that are usually organized as separate cost centers [9].

The "PLUG+PRODUCE" approach according to Hildebrand et al is based on the assumption that methods from the product development can also be applied in factory planning. Modularization and standardization are basic elements of this approach. Target of this method is the elaboration of a modular plant structure that is based on different categories of modules with specific tasks within the overall factory [10].

Eversheim and Neuhausen elaborated the concept "Modular Plant Architecture". Focus of this method is the design of a robust, standardized but also specialized and adaptive production structure. The approach works in three steps: analysis, design and evaluation. In the first step, different change drivers for the plant and their effects on the single factory elements are analyzed. After that, the modular concept is set-up, which is implemented in a company and situation specific reference architecture. The evaluation phase finally contains the forecast and influence analysis of change scenarios [11].

Schuh develops a concept for the modularization of production equipment. Based on approaches from product development, a concept is presented that enables a modular design of production equipment for the simple and fast exchange of different components. In this approach, change drivers for the specific equipment are analyzed in the first place before the modular structure is designed. In the last step, the modular concept is evaluated and the life cycle costs are calculated [12].

Klepsch analyzes the industrial building structure in detail in his approach. Key result is the development of a modular structure that separates the building into different sub-systems like roof, wall or infrastructure elements, which can be combined independently. This whole concept is based on a universal building grid [13].

Besides the factory hardware, the concept "Modular Manufacturing" by Tsukune et al also considers the software components within the factory. This approach especially focuses on the fast restructuring of production lines for the flexible manufacturing of many different products or variants in low volumes. A key enabler is the fast readjustment of the software that controls the robots within the production line [14].

The presented approaches give an impression regarding the diversity of modularization approaches that have already been developed. Most of these approaches focus on one specific field of interest within the company (e.g. equipment, building or software). Only few of them apply methods and tools from the product development, in which modularization approaches are already in use since the 1990s [15]. However, especially the cost and benefit evaluation of different modularization approaches has only been covered rarely in the existing approaches.

III. Practical and Theoretical Deficits

In this chapter, the main deficits in the elaboration of modular factory structures are presented from a practical and theoretical perspective. The mentioned deficits show the problems in the industrial practice as well as the main theoretical gap in the existing approaches. In the end of this chapter, the requirements of a new methodology for the elaboration of modular factory structures will be summarized.

A. Practical Perspective

The practical potentials and deficits of modular factory systems were investigated in the empirical survey "Excellent Factory Planning" 2014 by WZL of RWTH Aachen University [16]. The potentials of an application of modular structures within a factory planning approach were estimated with 15% from a cost perspective. Regarding the shortening of the project duration, the participants assumed 23% for Greenfield and 12% for brownfield projects (Fig. 1). These numbers show the high relevance of modular factory systems for the industrial application.

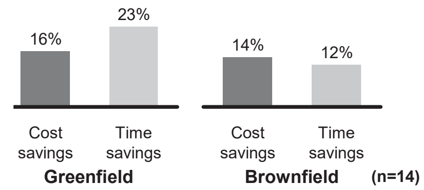

Fig. 1 Potentials of modular factory systems [16]

In the scope of this survey also difficulties within the application of these factory structures were covered (Fig. 2). The participants were asked where they see the main barriers for the application of this concept in factory planning. As main points the applicability in international projects, the complex cost-benefit analysis and the lack of specificity within the system were mentioned.

Another question was the existence of target processes for the initial definition of the modules. For this, the study results vary strongly. Especially smaller companies cannot always afford to have target processes because of their lower employee capacities.

In addition, the compositions of typical factory systems in the industry were analyzed. Most companies are e.g. in the middle between a fully specified legal standard and a normal checklist for the planning activities. Asking about modular factory systems, also many bigger companies have elaborated modular structures within their company but again smaller companies do not standardize their production planning activities in that manner.

The potentials of factory standardization or in detail modular factory structures were also investigated within the working group "Factory Planning" at WZL Aachen University, in which several big German companies are involved. In this working group, the companies especially mentioned the difficult cost-benefits analysis for such structures so that many decisions are made according to instincts but not calculations.

Summarizing the practical problems from the survey and the working group, the following four main challenges could be identified:

- International applicability of the standards in different countries around the world nonexistent
- Cost-benefit estimation currently only based on experience and instinct
- No universal target processes for the elaboration of modular factory systems existing

- Elaborated factory structures currently especially contain unique factory elements or solutions; variants of elements or modular structures are barely considered.

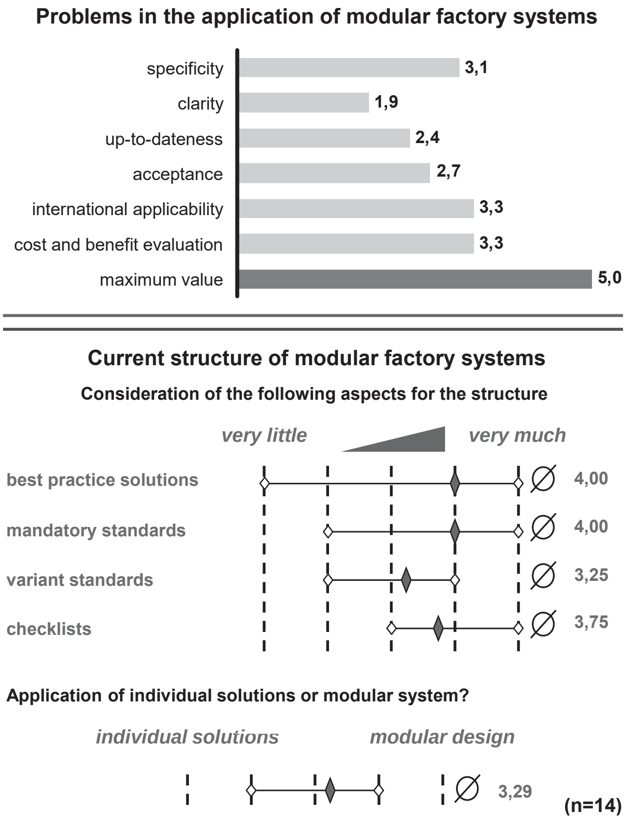

Fig. 2 Practical deficits of modular factory systems [8]

B. Theoretical Perspective

As mentioned in Section III A, especially the cost-benefit evaluation for modular factory systems is a big challenge for companies in practice. The implications of such a modular system are so wide-ranging that they affect nearly every department or section within a company (e.g. product program, supply chain, etc.). This makes a holistic evaluation of modular factory systems about all company areas nearly impossible.

In this context, a model for the holistic evaluation of the performance of a production system was developed by Nussbaum [17]. The model focuses on a complexity-based view on the production program considering also other categories. The performance of a production system is measured within the four categories product program, product architecture, and supply chain and production structure. For each category, dichotomies are specified by Nussbaum, which are then analyzed mathematically.

The perspective of this evaluation model is focused on the product program (as shown by the dark grey arrows in Fig. 3). One main application of this model is the investigation, how a higher product program complexity or diversity affects the performance of the overall production system within the single categories. The evaluation within the different categories is conducted separately and the impact of a change within one specific category on the other categories cannot be quantified mathematically. Only after a significant number of benchmarks and data collections that often take too much time or are not possible in the planning phase of a modular factory structure as no historical data is available in that phase.

A new approach must evaluate the costs and benefits of a new modular factory structure from a production perspective and analyze how this structure affects the product program, product architecture and supply chain (as shown by the light grey arrows in Fig. 3). In this way, for example different approaches or modular concepts (as e.g. product-oriented, personnel-oriented or production-segment-oriented modules) could be evaluated in the set-up of the modular factory structure.

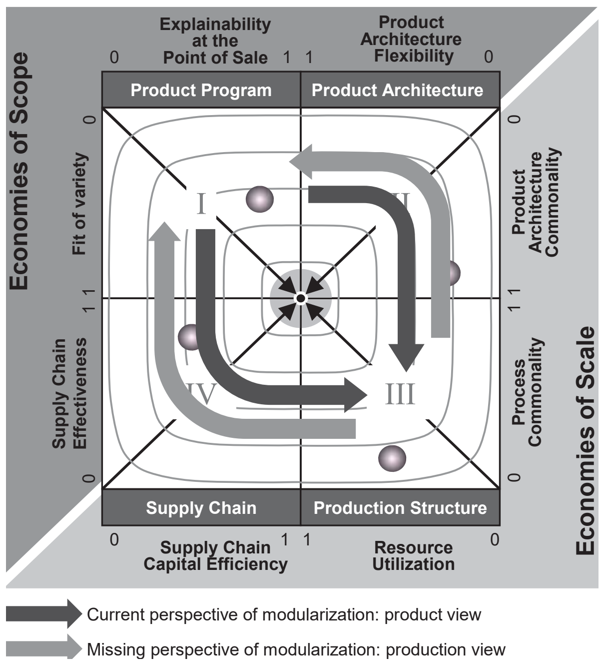

Fig. 3 Evaluation of overall production system performance [17]

One main problem in this model according to Nussbaum is that the different categories cannot be aggregated to one overall performance indicator for the production system. However, such an overall, mono-dimensional aggregation of the performance indicators within the different categories is essential for a holistic, integrated evaluation of the impacts of different modular structures. That is why a new approach should consider the measurability of the effects of the modular structure design on the overall performance of the production system.

C. Requirements for the Overall Methodology

Based on the described challenges from a practical and theoretical perspective, the main requirements for an overall methodology for the development of modular factory structures can be derived. These requirements are considered in the design of the methodology in Section IV:

- Integrative consideration of production system and industrial building on different factory levels

- Application of methods from product development and consideration of modularization approaches
- Consideration of small and medium-sized companies that do not have the capacities for complex and time-consuming modularization approaches
- Decision model required for the selection of factory elements with high standardization potential and for the choice between a standardized factory module or an individually planned factory element during the planning process
- Communication and implementation planning model for the modular factory elements required.

IV. Overall Methodology for the Development of Modular Factory Systems

In this chapter, a new methodology for the development of modular factory systems is presented. At first, the overall methodology is introduced before the basic models of the methodology are presented in detail.

A. Methodology Overview

For the overall methodology, a phase-oriented approach has been developed consisting of the three phases decomposition, synthesis and manifestation (Fig. 4) [18]. Key users of this methodology should be companies with several plants (probably across the world) and long-established structures. However, especially for industrial sectors that traditionally have a high number of small and medium-sized companies, which often use third parties as planning offices or general contractors when building new production facilities, this methodology can also be applied by those. In this case, the modular factory structure is not developed for one single company but for the completely industrial sector or branch (e.g. tool manufacturers, etc.).

Target of the first decomposition phase is the analysis of the existing diversity of the factory elements along the different plants. For this, the specific variants of the single factory elements have to be analyzed by the application of a "factory structure tree" that lists the different elements hierarchically. One further important step in this phase is the forecast of developments for the single factory elements. This can be a big challenge for a company as factories often have a life cycle of more than 30 years. For these forecasts especially big changes in the production technologies as well as other changes e.g. in the building or IT infrastructure have to be considered. That is why especially methods and tools from the discipline technology management must be applied in this phase.

In the second phase, the synthesis, the modular factory system structure is developed. In this phase, the different factory elements of the company´s plants have to be aggregated to one modular concept for the whole company. A basic step in this phase is the cost and benefit evaluation of different modular concepts. For the modularization, especially methods from product development can be applied.

The basic target of the third phase is the manifestation of the developed concepts within the company. This means that the final modular factory system has to be documented and communicated within the company. One other big task in this phase is the development of an implementation roadmap for the single factory modules. This roadmap summarizes for each module, in which factory or new plant it will be implemented over the next years. In addition, the main organizational issues as control and update processes for the modular factory system are defined in this phase.

Within the three phases, different methods from factory planning but also from other disciplines as product development or technology management are applied (as shown in Fig. 4).

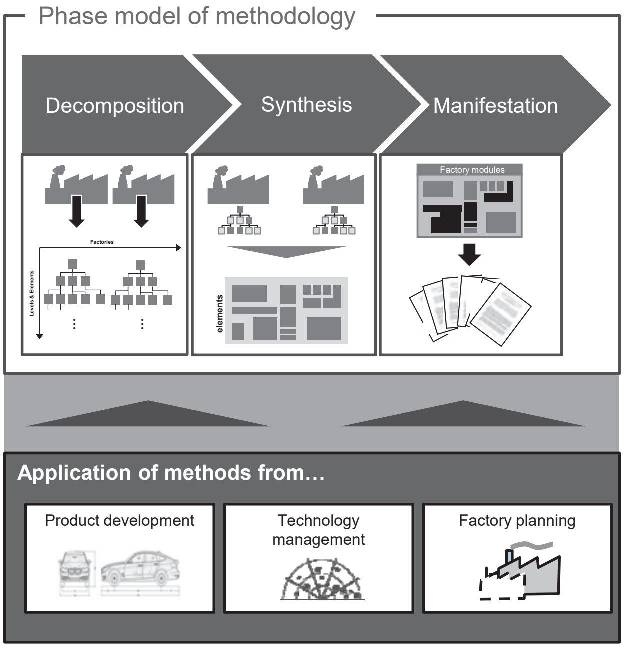

Fig. 4 Overview of overall methodology [18]

The key benefit of the methodology should be a shortened planning time for new factories at lower costs. In a theoretical model, this can also be analyzed in a simplified graph (Fig. 5): The costs and the duration of a planning project, which can be assumed as equivalent in a wider sense, are displayed on the horizontal axis, while the planning result is shown on the vertical axis. If all factory elements would be planned individually, a continuously rising curve with a decreasing slope would be the result. This decreasing slope comes from efficiency losses and over-engineering effects especially in the detailed planning work of a factory-planning project. The target of modular factory structures is now to enable certain surges in this curve by using off-the-shelf solutions in the project. In Fig. 5, for example a standard plant structure and building type are applied in the project. For those modules, no further planning efforts are required and the planning team can directly concentrate on the next step.

In the example only the plant structure and the building type are used as standard solutions as in every project there might always be circumstances that call for an individual solution. However, in the long-term the target for modular factory structures should always be that (nearly) every element is standardized to one or only a few different module variants.

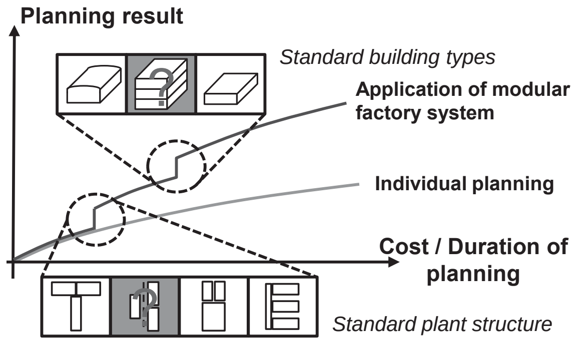

Fig. 5 Benefits of modular systems during planning phase [18]

B. Presentation of Basic Models

As presented in Section IV A, the overall methodology consists out of three different phases. Within these three phases, the methodology is based on four main basic models that are assigned to these three phases in Fig. 6. These four models and their part within the overall methodology will be explained in the following.

As mentioned the main task of the decomposition phase is the analysis of the diversity within the existing factory elements over different plants. For this, a structure tree for the factory elements is part of the methodology, which is derived from the variant tree in product development [19]. This structure tree supports the factory planners in the systematic examination of the different factory elements within the three categories "machinery & equipment", "organization" and "building and infrastructure". Within these categories, the structure tree uses different levels on which the analysis takes place. When all plants have been analyzed according to this structure tree, it is important to find out, which elements have the biggest communalities over all different plants. These communalities also have implications for the design of the modular factory system: Factory elements that have a very high communality should probably be considered as basic modules within the modular system, whereas elements with a lower communality should not be considered or only as adaptive modules with several variants.

The second basic model is the s-curve model for factory elements, which was originally invented and initially applied in technology management [20]. In this model, the basic context between the investment in research & development for a technology and the performance of this technology is analyzed mathematically. The result is a graph that has an increasing slope in the beginning and a decreasing slope in the end leading to an overall s-curve. In this model, the change to a new technology might be beneficial, when the investment for the old technology leads to low benefits regarding the performance, whereas for the new technology this relation is much more promising. A big challenge is the precise mathematical formalization of the graph and the correct definition of the performance indicator for the technology. This model can also be applied to factory planning, where most technologies have an even longer life cycle than in the normal scope of technology management.

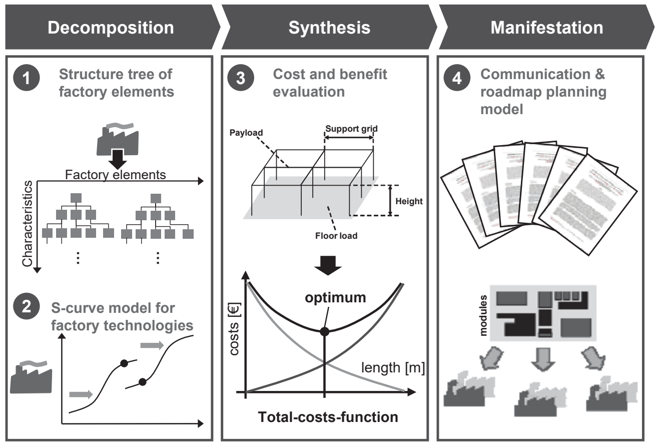

Fig. 6 Basic models of the methodology

As mentioned in chapter III especially the evaluation of costs and benefits of modular factory systems, which is conducted within the methodology in the synthesis phase, is a critical and challenging issue. For this, the methodology according to Nussbaum can be used but has to be adapted and developed further. One big challenge for the evaluation of modular factory systems is the definition of the "constitutional parameters" of the system. For this model, previous works regarding constitutional parameters of production systems can be used [21]. For factory elements, a methodology that is based on two steps has been developed. If a factory element shows a high communality over different plants, in a first step possible constitutional parameters must be selected. For example, if possible, constitutional parameters for the support grid of a factory building should be analyzed; at first, the basic functions of the support grid and the main characteristics must be elaborated. Basic functions of the support grid might be that it has to carry the factory roof and cranes, it has to enable placing machines between the pillars or perhaps it also has to be esthetic. These functions are enabled by the parameters of the support grid, which may for example be the height, material or grid dimension. By analyzing interdependencies between those parameters and the functions, possible constitutional parameters can be identified. Those parameters usually have a high impact on the functions of the particular factory element. In the second step, a profitability assessment for the potential constitutional parameters has to be conducted. If e.g. the grid dimension of the support grid is standardized as a constitutional parameter over all plants, it has several cost effects: For example, the maximum machinery length that fits inside the factory building is defined by this parameter. This analysis has to be conducted for all elements that have a high communality over different plants. As for the assessment, the cost effects of a factory element over the whole factory life cycle have to be evaluated, the approach of Burggräf can be considered for the basic cost model [22].

In the last phase of manifestation, a communication and roadmap-planning model is required. In this model especially the question, how the developed modular factory system can be communicated to the factory planners is of high importance. Several communication approaches can be useful for this according to the company´s philosophy (e.g. hardcopy folders, apps for smartphones, documentation in the intranet, etc.). A decision model is necessary so that a company can choose the best communication method. Additionally, the model has to cover the roadmap planning for the single factory modules, for which existing approaches from the product development can be used [23]. Result of this must be a precise plan, when which factory module will be applied in which plant. In addition, the introduction of new modules and updates of modules must be considered in this roadmap. Additionally, organizational processes for the updates and adaptions or for violations of the modular factory system must be set-up. For this, target processes that can be individually adapted to a specific company are part of this fourth model.

V. Conclusion and Outlook

To reduce costs and planning times in factory planning projects, the approach of modular factory systems has been developed. In this paper, the current state of the art and main practical problems were presented. In addition, the main research gap from a theoretical perspective, the holistic cost and benefit evaluation of modular factory systems, has been discussed. Based on this, the main requirements for an overall methodology have been elaborated. After that, a three-phased approach with its underlying basic models was introduced.

In the future, especially the automation of the application of the modular factory system will be a field of further research. For this a “factory configurator”, in which a company can put together a new plant in very short planning time, should be the target. In addition, the integration of the standard factory modules for a company within layout planning software and 3D planning solutions must be considered.

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