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An Analysis of Challenges and State of the Art for Modular Engineering in the Machine and Plant Manufacturing Domain

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Abstract: The increasing challenge to manufacture individual products in short periods of time makes a huge amount of machine and plant variants necessary and increases the effort in engineering as well as managing the variability. An adequate support system for modular engineering would increase reuse of variable parts of the machine or plant and, by that, enhance the engineering efficiency. Nevertheless, such a holistic support system is not yet available. This paper analyses the challenges to be addressed and derives a problem model to be investigated for future research to improve the engineering of modular machines and plants.

Keywords: Variant Management, Reuse, Engineering, Machine and plant manufacturing

1. INTRODUCTION

The engineering of machines and plants in special purpose machinery manufacture is strongly driven by individual customer requirements regarding a specific project, i.e. for each project necessary modules need to be identified and combined. In contrast, in series machine production numerous similar machines or plants are developed and manufactured. Due to the increasing demand to produce customer-specific, individual products, companies of the series machine production industry noticeably have to cope with the requirement to offer more and more variants of their machines or plants. Modularity and reuse, as well as variant management outline important challenges from the industry's point of view (Vogel-Heuser et al., 2014b). This results in a smooth transition from special purpose machinery manufacture to series machine production, referred to as individual series machine production.

Consequently, new challenges in engineering of machines or plants arise. To increase efficiency and to reduce the development costs, differences of variants regarding customer preferences or machine/plant features must be (efficiently) managed. For cost reasons companies are furthermore forced to ensure a high level of reuse within their software and hardware. Moreover, the market dynamics, i.e. changing customer preferences and requirements, necessitate a rapid adaptation of the product portfolio, e.g. through new variants of machines or plants normally developed based on a module library. For both aspects – variant management and increase of reuse – a well-structured approach is essential. Therefore, an engineering support system that supports in defining, retrieving and combining existing solutions seems to be a promising approach.

These challenges can be adequately addressed by current approaches only to a limited extent. On this account, this paper contributes to the engineering of machines and plants by analysing the indicated challenges in a structured manner (section 2), confronting them with the state of the art (section 3) and deriving a problem model (section 4) as a starting point for future research.

2. PROBLEM STATEMENT AND CHALLENGES

In this section, subsequent to introducing an application example (section 2.1), we formulate the problem statement (section 2.2) and derive challenges to be solved to provide support for modular engineering in the machine and plant manufacturing domain (section 2.3).

2.1 Application example: Pick-and-place unit

To illustrate the challenges of modular engineering, this section introduces an easily comprehensible, variant-rich system, namely a pick-and-place unit (PPU), cf. Fig. 1. The example is an excerpt of scenario 12 of the PPU demonstrator (Vogel-Heuser et al., 2014a) extended by the information provided by Vogel-Heuser et al. (2014b). Although being a bench-scale example, the PPU consists of diverse logistic units, which are standard units especially applied in the logistics domain in an industry-scale manner. The PPU thus is a representative application example for the challenges that arise in industry applications.

The PPU can be implemented in different variants – two exemplary ones are illustrated in Fig. 1 – and therefore fulfil different customer requirements. From the customer's point of view, the variants differ in the size of processed work pieces (small or large work pieces – either one size or any size), positioning capabilities (discrete and continuous positions) and environmental conditions (smooth and rough environmental conditions). From a developer's point of view, different *handling systems* are necessary to process the work pieces (*changeover arm* with *vacuum gripper* in *unit B* for small work pieces, *cylinder* with *vacuum gripper* in *unit A* for both small and large work pieces). For positioning capabilities, *position detection sensors* are used

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(*micro switches* or *inductive sensors* for discrete positions and *potentiometer* for continuous positions). Depending on the environmental conditions, developers must use appropriate sensors (*inductive sensors* or *potentiometer* must be used for rough conditions, all position detection sensors can be used for smooth conditions).

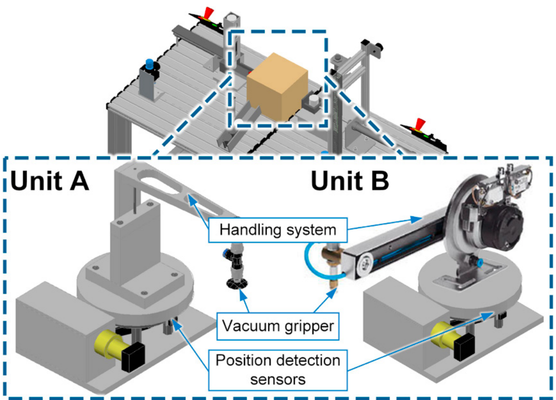

Fig. 1. Overview on the application example pick-and-place unit (PPU) – excerpt of scenario 12 in Vogel-Heuser et al. (2014a)

2.2 Problem statement

The increase of reuse and efficiency during engineering requires a separation into project-independent engineering activities in which engineering solutions are developed and made available for subsequent steps as well as project-related engineering activities in which solutions are combined and adapted for customer-specific projects (Jazdi et al., 2011). According to the Standard VDI/VDE 3695 (VDI/VDE, 2010), project-independent activities involve analysis, planning, realization and test/ approval of the solution parts. In the application example, the components necessary for the pick-and-place process are engineered during project-independent engineering, and then made available for any further engineering steps. Project-related engineering activities involve acquisition, planning, realization and commissioning phases (cf. VDI/VDE 3695). The reusable solution parts are hence retrieved and adapted for the specific engineering problem. For the PPU, adaptations in e.g. the unit's spatial dimensions and software parameters may be necessary.

Although available in novel Standards as VDI/VDE 3695, such a differentiation is not yet state of the art in the machine and plant manufacturing industry (Feldmann et al., 2012). Engineering solutions are often created from scratch or by adapting existing engineering solutions with high effort as reuse opportunities seem to be expensive and inefficient at first sight (Katzke et al., 2004). More sophisticated approaches – coming from research and partly from industry – provide repositories to make existing solutions available during engineering. Although decreasing effort and engineering costs as well as increasing reuse at first sight, these approaches may become complex: The larger the repository is, the higher is the effort to retrieve respective existing solutions, making approaches necessary to support the engineer in finding the appropriate module (Jazdi et al., 2011). An approach that supports the engineer by identifying appropriate parts of the solution and by (partly) synthesizing the engineering solutions for a specific problem therefore seems to be valuable.

2.3 Derived challenges

From the problem statement, to obtain adequate support in modular engineering, challenges to be tackled can be derived. These challenges are introduced in the following.

Challenge C1: Interdisciplinary modelling support

As machines and plants are interdisciplinary systems, i.e. engineers from multiple disciplines, participate in this process, an interdisciplinary modelling support needs to be available (Thramboulidis, 2013). To give an example, the PPU needs to be considered from different viewpoints: from a software viewpoint, module functionality and behaviour is focused, whereas a mere mechanical viewpoint purely considers structural aspects of the system. Hence, elements from those disciplines need to be represented in an adequate manner. Finally, as each part of the solution fulfils a respective functionality of the overall system, the solution parts' functionalities need to be considered and made available in the library.

Challenge C2: Support in managing model inconsistencies

To make things worse, adaptations of the engineering solution during design are often not synchronized, which leads to inconsistencies between the different models that are created during engineering (Herzig et al., 2011), and which makes a management of these inconsistencies necessary. In the PPU, a test case derived from a requirement model can define a minimum throughput to be realized by the PPU. A simulation model may predict the expected throughput, which could possibly violate the minimum throughput defined in the test case. Identifying such types of inconsistencies in interdisciplinary models needs to be supported. Moreover, although having a "common denominator" within the different models (such as the property *throughput* in both the test case and simulation model for the PPU), discipline-specific criteria for inconsistencies need to be analysed and supported. By identifying such inconsistencies, errors in the engineering process can be minimized and, hence, time and costs during engineering, start-up as well as during operation can be reduced.

Challenge C3: Differentiation between project-independent and project-related engineering activities

As argued beforehand, the increase of reuse and efficiency in engineering of machines and plants required a differentiation between project-independent and project-related engineering activities (Maga and Jazdi, 2012). Whereas project-independent engineering activities focus on increasing the reuse of available parts of the engineering solution to shorten project durations and reduce engineering costs, project-related engineering activities aim at identifying the appropriate composition of these parts to fulfil the customer's needs. This separation is illustrated in Fig. 2. During project-independent engineering activities, following an analysis of the solution elements that are required for possible systems, the requirements on the solution element are specified in a first step. Subsequently,