Formal computer-aided product family architecture design for mass customization

Martin Bonev a,*, Lars Hvam a, John Clarkson b, Anja Maier a

a Department of Management Engineering, Technical University of Denmark, Produktionstorvet, Build. 424, 2800 Kgs., Lyngby, Denmark
b Engineering Design Centre, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

1. Introduction

A growing demand towards higher product variety has been reported in many industries [1,2]. Acting upon this trend, companies aim at obtaining higher customer value and stronger economic benefits through rapidly responding to individual needs for customization [3]. Nonetheless, high and diverse product mixes are not always beneficial but often challenge manufacturers with a related increase in operational complexity and decrease in efficiency in sales, design, production and distribution [4]. Platforms and modules built into product family architectures have been reported to facilitate this trade-off [5]. In this context, architectures are defined as an abstract structural representation of the functional units and the corresponding physical components of engineering artefacts [6]. Their development is complex and long lasting and their performance can have wide-ranging effects on the success of manufacturers [7]. Designing architectures suitable for customization raises additional difficulties to organizations, since the right product composition and part compatibility needs to be ensured. With product configuration systems or configurators, manufacturers are able to handle these demanding requirements for information processing, storage and retrieval of feasible variant combinations [3].

Configurators are software-based expert systems that capture the generic architecture of product families in a computer model, through which users are supported in creating feasible product solutions with a minimum number of choices [8]. If combined with well-designed product family architectures, companies can utilize configurators to mass customize their offerings, i.e. to automate operational activities related to product customization and to increase their efficiency to a level which is close to mass production [9]. However, architectures per se are qualitative and current methods supporting their design and documentation are informal and limited [10,11]. Hence, it can be difficult to identify 'good' architectures during product design and to sustain their subsequent implementation in a configuration system. At the same time, configuration software vendors are of no help in this respect, as they are typically not interested in providing a transparent and easy way to create and communicate the
architectures, but rather emphasize consulting services around
their modelling and maintenance [12]. Consequently, with the
development progress of product families, software experts have
problems in keeping an overview of what had been implemented
in the computer model and verifying the obtained architectures
with domain experts, making it one of the main reasons why
designing and mass customizing products is still difficult to
achieve [13].

This paper presents a formal computer-assisted approach that
addresses the requirements for the design of product family
architecture as identified by academia and industry. Section 2 first
discusses existing approaches from both engineering and software
domains, to define a consistent architecture design framework.
Next, the challenges with conventional informal approaches are
discussed and requirements for a formal support method are
developed. Section 3 elaborates and further extends existing
modelling techniques and relevant formal architecture support
measures. In Section 4 a formal approach is presented and
complemented with a case study of a major plant and machinery
provider of highly customizable products, to develop a concrete
eXample on a real world problem. The introduced approach
combines the capabilities of the utilized configurator with
automatically generated grammar graphs representing the imple-
menced architectures. The graphs are modelled with an integrated
design model (IDM), using the suggested extended modelling
techniques for generic structures. A developed IDM tool is further
employed to assist domain experts in synthesising feasible
architectures and to evaluate their structural characteristics
computationally through a series of metrics, potentially leading
to better solutions. Finally, Section 6 concludes with an assessment
of the proposed approach.

2. Relevant literature

To evaluate the limitations of existing approaches to architec-
ture design for mass customization, a literature review on relevant
frameworks, methods and modelling techniques is performed and
requirements for a formal method are developed.

2.1. Approaches to architecture design in engineering and software
development

The design of architectures and their subsequent implementa-
tion in configurators involves domain experts from different
departments and often physically disconnected teams. Several
researchers have acknowledged the related organizational chal-
lenges and have proposed methods on how to arrange correspond-
ing activities in a more systematic manner [14–16]. In engineering
domains Pahl et al. [17] address architecture design on several
stages, from formulating customer needs to the construction of
embodiment and detailed design. Corresponding to these different
phases of development, Jiao et al. [18] argue for an architecture
modelling framework which in addition considers several views of
a product. At the same time frameworks dealing with architecture
design for expert systems typically fall within the area of software
systems and base their methods on the life-cycle of object-oriented
software development as introduced by Booch [19]. Booch’s
object-oriented procedure was originally developed to handle the
complexity of large software projects by breaking down the
development work into phases of object-oriented analysis, design,
implementation and maintenance [19]. The transformation from a
real world design into a computer model is organized in several
steps, where the observed reality is gradually abstracted and
formalized [20]. To enable the representation of a large number of
physical artefacts with components and variant combinations,
related frameworks commonly build upon methods for modelling
software architectures using the unified modelling language (UML)
[21].

Although the UML standard proved to be particular useful for
defining entire product families, its application within engineering
design remains limited. In consequence, synergies on coinciding
aspects of architecture design are seldom achieved. For example,
the challenge of modelling different architecture views has been
repeatedly addressed within the two domains and has resulted in
comparable outcomes [18,22,23]. Moreover, advancements within
engineering design are seldom adopted to software design and vice
versa, in particular with regard to the formal computational
management of structural properties in complex architectures
[24]. Second, the development of a product family architecture for
expert systems is often organized within IT and product data
management departments. The process is regarded as a liberally
new modelling approach which is detached from any preceding
design activities of the product development phase [25]. This
means that in praxis the design of architectures is not coordinated
across the organization, leading to computer models which are
very likely to differ from the original design intent of the engineers
[13]. Especially for more complex products, this lack of consistency
increases the risk of providing undesired product variety to the
market [26]. As a benchmark report with more than 300 manufac-
turers of custom tailored products reveals, the top performing
companies with engineering intensive portfolios try to overcome
this coordination burden by better involving development
engineers in the architecture design process for their configuration
systems [27]. This suggests that a more integrated approach to
mass customization is needed, which considers equally both the
architecture design process and the subsequent implementation
into configuration systems.

2.2. Challenges with conventional informal architecture design
methods

Fig. 1 illustrates how a consistent framework of the architecture
design process and its transformation into a computer model may
be organized. The model is based on the Wyatt et al. [11] generic
scheme for architecture design in engineering, and combines this
with the discussed transformation into a computer model. The
focus of this paper is indicated by the grey area in the model, where
design aspects from engineering are incorporated with the
software domain of configurators. The procedure is initiated by
a design or handling problem and ends with a customized solution
created by the user of a configuration system. As expressed in the
model, supporting methods can be informal, relying on subjective
interpretations of domain experts, or formal, involving codable and
systematic procedures. The two alternative approaches may be
organized along a five phase model of exploration, generation,
evaluation, implementation and communication, which is based on
the established development model of design science [28].

In analogy to Wyatt et al.’s [11] architecture design framework,
the informal approach can be described as follows:

- **Exploration** helps engineers to examine the handling of existing
design or the work on a new design problem. Typically, product
information can exist in many different formats, such as
diagrams, tables, formulas, computer aided design (CAD) files,
bills of materials (BOMs) etc. Different departments within a
company may even have their own representations of products.
By **abstracting** the relevant product information (1), engineers
develop an understanding of possible architectures (2)

- Based on a created understanding of possible architectures,
engineers **generate** a specific family architecture in the form of an
analysis model, which may be the same as previous solutions and
further contain errors (3). Discussions on the product architecture
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