Establishing a maturity model for design automation in sales-delivery processes of ETO products

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Abstract

Short delivery times are considered a competitive advantage in the engineer-to-order (ETO) sector. Design-related tasks contribute to a substantial amount of delivery times and costs since ETO products have to be either fully developed or adapted to customer specifications within tendering or order fulfillment. Approaches aiming at a computerised automation of tasks related to the design process, often termed design automation or knowledge-based engineering, are generally regarded as an effective means to achieve lead time and cost reductions while maintaining, or even improving product quality. In this study we propose a maturity model as a framework for analyzing and improving such activities in ETO companies. We contribute to the literature in being the first to investigate design automation in the ETO sector from a maturity perspective. Beyond that, we extend the extant literature on design automation, which is of a highly technical nature, by providing a framework considering organizational and managerial aspects. The findings indicate that five different levels of maturity can be achieved across the dimensions strategies, processes, systems, and people. Empirical cases give insight into these different levels. Our investigation draws from extant literature and a comparative case study involving four companies over two years.

Key words engineer-to-order, design automation, knowledge-based engineering, product configuration, maturity model

1. Introduction

Fast and cost-efficient tendering and order execution processes are considered as sources of competitive advantage in the engineer-to-order (ETO) sector [1–3]. Since ETO products either have to be fully developed or adapted to customer specifications within tendering or order fulfillment [4,5], design-related tasks contribute to a substantial amount of delivery lead times and costs. Approaches aiming at computerised automation of tasks related to the design process, often termed design automation or knowledge-based engineering (KBE), are generally regarded as an effective means to achieve lead time and cost reductions while maintaining, or even improving product quality [6–8]. For example, case studies conducted by Raffaeli et al. [9] and Frank et al. [10] found that design automation based on integrating product configurators and CAD systems may result in a reduction of the engineering time by up to 90%. Empirical evidence further suggests that the introduction of sales configurators, which constitutes as an element of design automation, contributes to better on-time delivery, a decrease in personnel efforts and quality improvements along both product and process dimensions [11,12].

While technical aspects of design automation (e.g. system architecture, product modeling) are well researched [9,13–15], studies related to organizational and managerial requirements of design automation are hardly available [16,17]. Researchers particularly emphasize the need for a framework guiding the design automation process and supporting the identification of design automation opportunities [7,16]. More specifically, Cederfeldt and Elgh [16] in a sample of eleven ETO manufacturers identified *scope of implementation* (e.g. implementation of sales configurators, engineering configurators, CAD systems, or spreadsheet macros*)* and *how far to push the automation level* as topics requiring additional research. Well-established concepts associated with maturity models are relevant to these issues, but the review presented later in the paper shows that these have not been adequately adapted to either design automation or ETO situations. Beyond the shortcomings identified in the literature, discussions with company representatives brought to light that managers are often uncertain which steps to take in approaching design automation.

To fill this gap, the present paper examines the following research question: *What stages do ETO companies undergo in automating their design processes and how can we describe them?* We base our investigation on a comparative case study with four ETO manufacturers from the mechanical engineering sector. The concept of the maturity model was selected to guide the investigation due to its suitability for describing organizational development paths [18,19] and supporting transformation processes [20].

This study contributes to the literature in being the first to investigate design automation in the ETO sector from a maturity perspective. Beyond that, it extends the extant literature on design automation, which is of a highly technical nature, by providing a framework considering organizational and managerial aspects. It further provides companies with a step-wise guideline on how to approach design automation in sales-delivery processes as a means to foster a competitive advantage. Following Verhagen's [7] call for research, we further suggest that our maturity model can be used as an instrument for assessing design automation opportunities.

This paper is structured as follows. Section 2 provides an overview of the related work and state of the art. Section 3 describes our methodological approach and introduces the empirical setting in which we conducted our research. In Section 4, a maturity model for design automation is conceptually drafted, thereafter empirically refined through a comparative case study and finally validated. Lastly, the conclusion section highlights the theoretical and managerial implications and proposes opportunities for further research.

2. Related work and state of the art

2.1 Engineer-to-order

A number of papers have sought to define and categorize ETO situations, as well as give insight into their complex nature. Gosling and Naim [2] define an ETO supply chain where production is customized for each order and where the customer penetrates into the design phase, often operating in project specific environments. Since ETO products either have to be fully developed or adapted to customer specifications [4,5], engineering tasks have to be conducted within tendering or order execution. This can lead to a range of co-ordination issues in terms of integrating engineering and production [21].

The ETO sector encompasses a broad range of industries, including mechanical engineering, construction, and ship-building. A number of ETO archetypes may also be identified, based on volume and the amount of order specific engineering work to be performed [22]. Customers in this challenging sector often wish for lead times to be short and are not willing to pay high price premiums [23–25]. Hence, companies that operate in an ETO environment face the difficult prospect of undertaking order-driven design and engineering activities while customers wait impatiently, often making last minute requests for changes. This leads to unpredictable work flows, 'rush jobs', out-of-date information, and distorted delivery dates [26].

From an engineering design perspective, ETO might be considered as the extent to which orders penetrate the scientific-technical flow of design activities [27]. Hence, we might consider a spectrum between pure 'engineer-to-stock', where designs are held in stock, to pure ETO, where new designs must be developed [2]. Despite this continuum being well recognized, the appropriate design approach along it has not been addressed comprehensively in the ETO literature.

Design automation is predominantly seen as an approach for minimizing the effort required for repetitive design tasks [7,13,16]. However, engineering ETO products encompasses the execution of both repetitive and creative design tasks. Consequently, product structures distinguishing between components that already exist and therefore can be reused in a repetitive manner and components that have to be engineered for a particular order are a prerequisite [28,29]. A review of the literature shows that various terminology has been applied to break down the structures of ETO products. A proliferation of terms from the design literature seek to describe ways of responding to the challenge of configuring and designing to customer order. Examples include modular design [30], platform designs [31], and configuration design [32]. Jiao et al. [33] show the considerable range of terms that have emerged. Further, the terms 'common features', 'base product' [28]', 'fixed components' [34] and 'standard parts and modules' [35] have been proposed to describe the standard components of an ETO product. The terms 'parameterized features', 'reused variants' [28], 'configurable components' [34] and 'generic product structure' [35] all describe its configurable components. To describe the components that are truly engineered for a specific customer order the terms 'special features', 'new components' [28], 'special components' [34], 'parts which are developed based on norms and standards' [35] and 'white spots' [36] can all be found. In this paper, we use the terms *standard components*, *configurable components* and *special components* to distinguish between the different components of ETO products.

2.2 Design automation

The term design automation has its origins in the electronics sector where it has been used since the early 1970s to describe the automated design of circuits and electronics chips [37,38]. More recently, the term has increasingly been applied when referring to the automation of design-related tasks in the field of mechanical engineering [6,7,10,13,16,39]. There exists no general consensus on the definition of design automation in the literature (see [7,10,16,29,40]). In this paper we apply the definition of design automation by Cederfeldt and Elgh [16] as '*computerized automation of tasks that are related to the design process through the implementation of information and knowledge in tools or systems.'*

A broad range of literature related to the techical aspects of design automation exists (see Elgh [6] for a detailed review), whereas literature discussing the organizational and managerial aspects is scarce. Both Elgh [6] and Cederfeldt [16] give recommendations for planning design automation in ETO companies. While Elgh [6] proposes an information model for design automation in quotation preparation, Cederfeldt [16] conducts a study with ETO manufacturers on the need and perceived potential for a design automation framework. In describing the move from ETO to mass customization, Haug et al. [41] identify five dimensions (product variety, customer view, manufacturing costs, business purpose, configurator challenge) which they regard as relevant for deciding to what extent to standardize and automate.

Scholars in our field of study regard design automation for ETO as highly similar to KBE [7,42,43] or respectively regard KBE as one of its core sub-disciplines [10]. Typically, the automation of design processes for highly customized products is seen to encompass developing and implementing the following IT applications: sales configurators [11,44,45], engineering or technical configurators [10,41,44–46], as well as the linking of those with CAD systems [9,10]. Although product lifecycle management (PLM) systems are generally regarded as enablers for sharing product data along entire supply chains or product lifecycles [47], there exists no consensus on how well these systems are equiped to cope with the challenges the ETO environment presents. While Hicks and McGovern [48] found that some functionalities of PLM systems are applicable for ETO products, it still remains to be determined how big their overall value is when lifecycles are short and volumes low. An empirical study conducted in the shipbuilding sector confirms that PLM systems have been designed with predominantly assemble-to-order (ATO) and make-to-order (MTO) enivronments in mind and require adaptions for a successful implementation in ETO environments [49]. Additionally, Hani et al. [50] report that PLM systems do not sufficiently suport the reuse of design process knowledge through identifying appropriate workflows within previous projects.

Literature describing how standard and configurable components, which are characteristic for MTO products, can be stored in IT applications and later retrieved for reuse abounds (see Zhang [51] for a review). However, these approaches neglect the special requirements of the ETO environment, such as the execution of creative design tasks for the development of order-specific solutions. Silventoinen et al. [52] conducted an entire study exploring and classifying the factors hindering an information reuse in ETO companies. In describing the ETO situation, McGovern et al. [53] state that a limited reuse of engineering designs is not uncommon. They further refer to anecdotal evidence highlighting that designers appreciate the task of developing new designs. Further, Brière-Côté et al. [28] report that project-specific data tends to be regarded as transient and is therefore often not linked to the lifecycle of the product family. In our literature review, we could identify first attempts targeting the design automation challenges characteristic for the ETO environment. Brière-Côté et al. [28] propose a product structure concept systematically promoting the reuse of order-specific solutions. Kristianto et al. [54] develop a system level configurator that processes incomplete configurations and engineering changes.

In the ETO environment, design automation can be applied either for the generation of conceptual new designs as part of new product development or in later project stages, such as tendering and order execution, for the development of detailed designs linked to specific customer projects. In the following, we refer to design activites conducted within tendering and order execution that are linked to customer projects as 'order-specific engineering'. This paper investigates design automation in sales-delivery processes while design automation in new product development is not within its scope. Our main rationale for excluding design automation in new product development from this investigation is that design automation in this phase encompasses very similar challenges for a broad variety of product types. On the other hand, the ETO environment has very unique requirements for design automation within tendering and order execution.

2.3 Maturity models

The Oxford English Dictionary describes maturity as the *state of being complete, perfect, or ready* [55]. Maturity models (MMs) are widely applied tools for assessing the maturity of organizations and provide a framework for process improvements or benchmarks [19]. They usually consist of a series of stages representing an anticipated, desired, or logical organizational evolution path [18] with the bottom stage describing a very low degree of maturity and the highest degree of maturity located at the top. Besides generic MMs, which are suitable for a very broad field of applications, such as the Quality Management Maturity Grid [56], the Capability Maturity Model [57], or the Capability Maturity Model Integration (CMMI) [58], models explicitly focusing on narrower defined domains can be found in the literature (e.g. [20,57,60]).

In recent years, efforts to generalize the MM development process aiming at a theoretically sound and replicable MM design have been made (see [18,61–63]). The proposed guidelines for MM development include a *problem identification phase* in which purpose and scope of the model are determined, a *model development phase* in which model and assessment instruments are defined, and an *implementation and validation phase* in which the model is evaluated based on empirical cases.

We present an overview of the extant maturity-related literature in the realms of ETO and design automation in Table 1. There exists general consensus that MMs can contribute to an analysis of the ETO environment but require some tailoring to unlock their full potential [48,64,65]. In none of the papers did we find such a tailoring. Tiihonen and Soininen [66] conducted a survey on methods, practices, and tools supporting product configuration tasks. They conclude that companies can be at different stages regarding the use of product configurators and propose the MM as instrument for understanding and improving configuration processes. Cederfeldt and Elgh [16] and Cederfeldt [17] conducted empirical studies in the field of design automation. They associate potential for design automation with a company's degree of product and process maturity. Making the link between ETO and design automation is not within the scope of any of the reviewed papers.

Table 1: Maturity-related literature in the realms of ETO and design automation

Author	Title	Research design and method	Contents	Contribution to maturity-related aspects
ETO				
Veldmann & Klingenberg [48]	Applicability of the capability maturity model for engineer-to-order firms	Empirical (single case study)	• evaluation of applicability of CMMI on ETO companies	• concludes that CMMI has to be enhanced to become applicable for ETO companies (e.g. logistics, construction and maintenance are not sufficiently covered)
Hicks & McGovern [49]	Product life cycle management in engineer-to-order industries	Conceptual	• analysis of characteristics of ETO companies (e.g. markets, products, internal processes and supply chains)	• states that MM is a suitable tool for managing the ETO life cycle
Kärkkäinen & Myllärniemi [50]	Maturity assessment for implementing and using product lifecycle management in project-oriented engineering companies	Empirical (multiple case study)	• analysis of the potential of a PLM maturity assessment in ETO companies	• PLM maturity assessment based on an existing PLM MM is conducted • outlines that generic MMs require tailoring to become applicable in ETO settings
Design automation				
Tiihonen et al. [51]	State-of-the-practice in product configuration – a survey of 10 cases in the Finnish industry	Empirical (survey with 10 companies)	• empirical study on methods, practices and tools that support product configuration tasks	• states that companies are at different levels of maturity in respect to product configuration • proposes MM as (1) suitable tool for assessing configuration processes and product data management and (2) improvement roadmap for product configuration
Cederfeldt & Elgh [16]	Design automation in SMEs - current state, potential, need and requirements	Empirical (questionnaire with 11 companies)	• empirical study identifying the perceived potential for, current state of, and requirements for design automation from a SME perspective	• focus on process maturity (see Cederfeldt 2007)
Cederfeldt [17]	Planning design automation - a structured method and supporting tools	Empirical (questionnaire/ multiple case study)	• development of a structured method for planning design automation	• focus on process and product maturity: attributes the potential for design automation to a company's degree of product and process maturity

3. Methodology

As outlined in the previous section, the literature proposes a variety of guidelines and frameworks for developing maturity models. We decided to use the four-step guideline for MM development introduced in Neff et al. [20], which is rooted in the procedure model developed by Becker et al. [18]. As presented in Figure 1, we slightly adjusted the guideline to make it more applicable to our specific research setting.

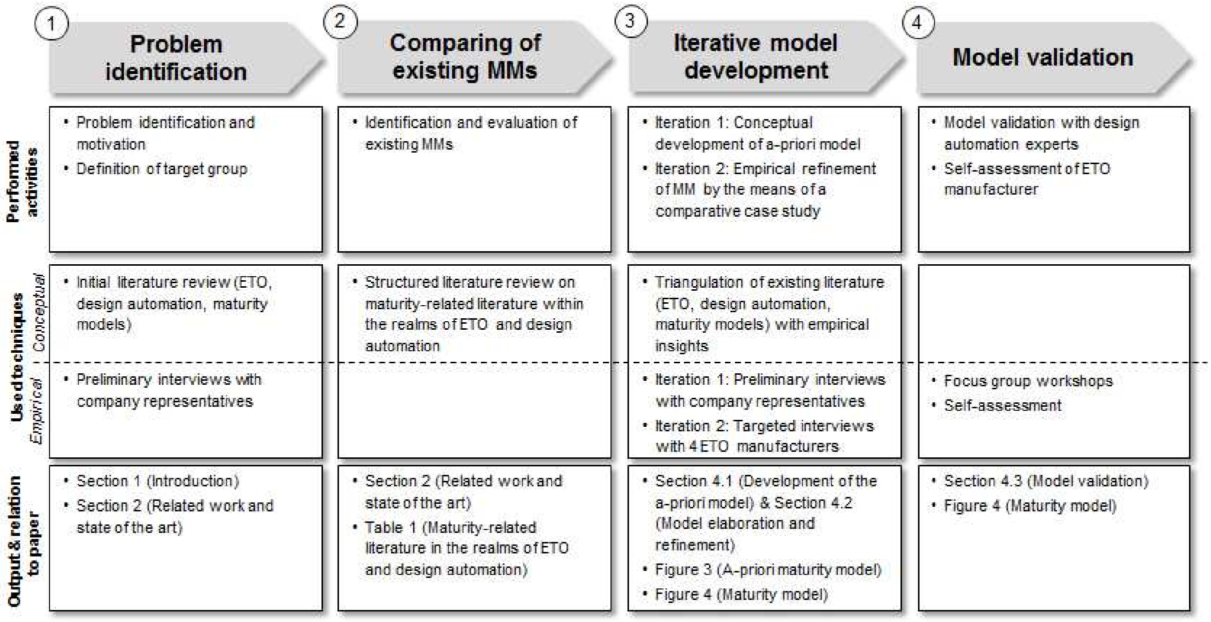

Figure 1: Guideline for maturity model development (based on [18,20]*)*

Prior to MM development, the relevance of the problem that the model is meant to address has to be demonstrated, and the target group of the model should be defined (*step 1: problem identification*). As presented in Section 1 and 2, both empirical evidence gained from preliminary interviews with company representatives as well as an initial literature review revealed that the automation of design processes is crucial to enhancing the competitiveness of ETO manufacturers. Yet both the extant literature as well as empirical insights obtained from company representatives confirmed that there is a lack of established frameworks or guidelines assisting ETO companies in automating their design processes.

According to Becker et al. [18], the need for a new MM must be confirmed by an analysis of the existing models *(step 2: comparison of existing MMs*). We conducted a structured literature review to identify the MMs predominant in our field of research. As search terms we used ‘maturity model’ combined with ‘engineer-to-order’, ‘design-to-order’, ‘design automation’ or ‘product configuration’. Major databases, such as Science Direct, Emerald, Pro Quest, and Google Scholar, were used to search for related works. Since we were unable to identify any domain-specific MMs within our field of research, we choose to broaden our research scope to maturity-related literature within the realms of ETO and design automation. Based on a content check, we determined which publications to consider relevant with respect to our research interest. Within the relevant papers, we conducted backward and forward searches with the objective of detecting additional material. In total, we identified six publications (see Section 2, Table 1) that we analyzed in detail.

MMs should be developed iteratively (*step 3: iterative model development*). Our approach consisted of two iterations. In the first iteration, we conceptually developed our a-priori model based on the requirements we had previously derived from both the literature review and preliminary interviews with company representatives. In the second iteration, we empirically refined the model by means of a comparative case study with four ETO manufacturers (see Table 2). At each of the companies, we conducted targeted interviews following an interview guideline (see *Appendix A*). As part of the interviews, we introduced our a-priori model to illustrate the study scope and to provide our case study partners with a framework that allowed them to describe their path towards design automation in a structured and comparable manner. We recorded all interviews and later reduced their contents into categories along our five-level analysis frame, which contributes to both within-case and cross-case analysis [65]. By doing so, we were able to identify common maturity paths across the companies. For example, our data showed that product structures are always established before sales or even engineering configurators are introduced.

Table 2: Case study companies

Company	Corporate division	Number of employees[1]	Turnover in million €[1]	Number of units sold	Department in charge of order-specific engineering (incl. number and qualification of employees)	Preliminary interviews[3] (*1st round of interviews*)	Targeted interviews[4] (*2nd round of interviews*)	Supplementary data
ALPHA	Environmental simulation	2,000	>250	200[2]	Engineering (45 full-time employees: engineering degree from universities of applied sciences or vocational training)	-	2 interview participants (Technical Director; Head of Control Engineering); 5h in total	-
BETA	Turbomachine	160	>100	10[1]	Engineering (75 full-time employees: 90% with university degree in mechanical/ electrical engineering; 10% with vocational training)	1 interview participant (Director of Engineering); 3h in total	1 interview participant (Director of Engineering); 3h in total	Participation in company meetings (>50h in total), process mappings, company data
GAMMA	Asphalt mixing plant	n/a	n/a	200[1]	Product development and engineering (n/a; engineering degrees from universities/ universities of applied sciences or vocational training)	4 interview participants (Director of Development Core Parts, Technical Manager Paver, Technical Director China, Technical Director Italy); 9h in total	1 interview participant (Product Manager); 3h in total	Participation in company meetings with various company representatives (>90h in total, process mappings, company data
DELTA	High-rise elevator	250	n/a	2,000[1]	Application Engineering (n/a; bachelor degree in mechanical/ electrical engineering or vocational training)	4 interview participants (Manager Engineering Switzerland, Manager Engineering China, Director Product Line Management, Engineering Director); 12h in total	1 interview participant (Director Product Line Management); 3h in total	Participation in company meetings with various company representatives (>150h in total), process mappings, company data

As emphasized in Wendler [19], the development of a meaningful and useful MM should conclude with model validation *(step 4: model validation)*. As shown in Table 3, our approach for model validation was twofold: First, we conducted focus group workshops with design automation experts. Second, we requested a company that had not participated in the model development to conduct a self-assessment with our model. Based on the workshop results, we further adjusted and refined the model.

Table 3: Participants of focus group and self-assessment workshops

Company	Corporate division	Number of employees[1]	Turnover in €[1]	Self-assessment workshops[2]	Focus group workshops[2]
EPSILON (industry-oriented research firm specialized in design automation)	Design Automation	9	n/a	-	3 participants (Managing Director, Head of Design Automation Division; Research Engineer); 4h in total
ZETA (large corporation offering a broad range of ETO products)	Corporate Technology	6,000	n/a	-	3 participants (Program Manager Modularization, Program Manager Product Portfolio Management, Researcher); 2h in total
ETA	Elevator	200	40	1 participant (Director Product Development and Engineering); 3h in total	-

[1] figures of 2014 for the division [2]conducted in 05/2015

4. A maturity model for design automation

As described in the methodology section, we selected an iterative approach for developing the maturity model. This section describes how initially the a-priori model was designed, thereafter empirically refined with multiple case studies and finally validated. We believe that an alternative could have been the development of a stage gate model [68] for design automation. However, stage gate models are mainly applied in the context of new product development, and the conventionally used stages are not entirely suitable for describing sales and order execution processes in the ETO environment.

4.1 Development of the a-priori model

As a starting point, we developed a rough a-priori model (see Figure 2). For the a-priori model, we drew from concepts underlying CMMI [58] to define the different levels of maturity. As the literature shows the CMMI is a very popular foundation for the development of new maturity models (according to Wendler's mapping study [19] 75% of established maturity models are based on the CMMI). An alternative would have been the use of the stages proposed in the Quality Management Maturity Grid [56]. However, we considered the terms used to describe the stages in that model such as "awakening" or "enlightening" not as appropriate for our purposes. The three categories 'strategies', 'processes' and 'systems' proposed in Österle [69] were initially applied as dimensions. We opted for developing a multi-dimensional instead of a one-dimensional model. The results obtained from multi-dimensional models are much more suited to letting organizations gain awareness of their strengths and weaknesses and providing guidance for improvements [63]. Later, the model was extended by the 'people' dimension following De Bruin and Rosemann [70] since empirical evidence gained in the first round of interviews revealed that the mindset and abilities of employees have a strong impact on the level of design automation a company can achieve.

To communicate our understanding of design automation to the case study partners, we predefined the two extremes of the model. As shown in Figure 2, level 1 implies that effectively no standardization and design automation has been put into practice. The customer is free to define the specifications of his order since the solution space is completely open. Processes are ad-hoc, and hardly any systems supporting tendering and order execution are available. Level 5 is characterized by specified and implemented processes and systems that allow full automation of the tendering and order execution processes. Since a fixed solution space is regarded as a prerequisite for a full automation [46], we argue that in practice only fully configurable products (MTO) can reach level 5. By definition, the solution space of an ETO product has to remain at least partially open and therefore the maturity of an ETO organization can at most converge towards level 5.

	Level 1 – Initial –	Level 2 – Managed –	Level 3 – Defined –	Level 4 – Quantitatively Managed –	Level 5 – Optimising –
Strategies	• Open solution space; customer is free in defining order specifications • No performance management: budget and schedule are often exceeded				• Fixed solution space that is regularly adjusted to customer needs • Performance measurement used for continuous improvements
Processes	• Ad-hoc processes, occasionally chaotic				• Fully defined and coordinated processes
Systems	• No IT systems for tendering and order execution exist • Data is collected randomly				• Fully integrated IT systems for tendering and order execution in place • Rigorous and automated data collection and analysis
People	• No clear roles and responsibilities • Success depends on individual effort and heroics				• Clearly defined roles and responsibilities • Success depends on collective effort and comprehensive integration of tasks and roles

Figure 2: A-priori maturity model

4.2 Model elaboration and refinement

To empirically elaborate and refine the a-priori model into a full-scale maturity model, a comparative case study involving four ETO manufacturers was conducted. The investigated products (testing chamber, turbomachine, asphalt mixing plant, high-rise elevator) of all four participating manufacturers have been on the market for more than 30 years and can therefore be considered mature and well-established. All four companies serve both developed, mainly Central Europe, as well as emerging markets, particularly China. Since our cases demonstrate very similar degrees in product and market maturity, we believe that they are not suitable for investigating the impact of product and market maturity on design automation. Instead, our unit of analysis is the corporate division and our study investigates *'what stages ETO companies undergo in automating their design processes'*. First, we present the four empirical cases individually. Second, we aggregate our findings by means of a cross-case analysis and from there elaborate and refine the model.

Company ALPHA

ALPHA participated in the case study with its site producing special testing chambers, part of the environmental simulation division. The division develops and produces testing chambers in five countries at seven different locations. In 2014, the site participating in our study built 200 special testing chambers, each requiring 500 hours of engineering on average.

Level 1 – Ultimate freedom

For a long time, the management at ALPHA regarded testing chambers as one-of-a-kind products and made no efforts towards standardization and automation. A consistent product structure did not exist, and both engineering and production departments frequently customized products during order execution. Most employees had the mindset of craftsmen and enjoyed following their own processes and ideas when engineering products. Engineers generally preferred to design everything from scratch instead of using existing solutions. Plus, they were often not aware of the order-specific solutions their colleagues have developed in the past since no proper database with search functionalities existed. A systematic retrieval and reuse of similar projects and/or components tends was almost impossible. Consequently, the company had problems with costs, quality, and lead times.

Level 2 – Product standardization (today)

In 2010, the top management at ALPHA changed and it became a core objective of the new management team to increase the profitability of the division. The Technical Director reported that an essential step towards this objective was the definition of a consistent product structure. He explained: *'Many of our projects did not really require order-specific engineering. Instead, a well-elaborated, modular product structure would have allowed a frequent reuse of components.'*

When asked for the expected benefits of product standardization, he explained: *'We expected a standardization to result in cost and lead time reductions as well as quality improvements. It was also supposed to allow us to build the exact same products at different locations.'* He then continued: *'Today, we still have some difficulties with the new product structures. It takes our engineers more time to combine our new templates for standard components instead of simply using old projects and adapting them. However, this should not be an issue anymore once our product structures have been properly implemented in a configurator.'*

Outlook

At the time of investigation, ALPHA stored its product structures in an ERP system. It is expected that sales might need a configurator to support tendering in the future. The Technical Director further reported that some departments might require restructuring due to the product standardization. While today ALPHA has a large department solely responsible for the order-specific engineering, in the future ALPHA will have to distinguish between the task of defining standard/configurable components and the task of executing the engineering for individual orders.

Company BETA

BETA is a large multinational corporation that participated in the case study with one of its turbomachine divisions. The division was founded less than 10 years ago and shows characteristics of a start-up (e.g. high growth rate, low formalization and routinization of processes, no established product portfolio). In 2014, the division received orders for ten turbomachines, each requiring 11,500 hours of order-specific development and engineering on average.

Level 1 – Ultimate freedom

The turbomachine R&D department was founded in 2008. In its beginnings, very limited customer intelligence that could be used for a delimitation of the solution space was available. Product structures were not fully defined and processes were ad hoc, partially inefficient, and redundant. A large number of design iterations and subsequent design reviews were required for each order.

Level 2 – Product standardization

Initially, BETA structured its machine types into different performance clusters and defined standardized components covering the clusters. When asked for his motivation for product standardization, the Director of Engineering at BETA explained: '*Beyond a reduction in costs and lead times, standardized product structures allows us to compare the prices of purchased parts and bundle orders for parts of a similar or identical design. Plus, I believe that consistent product structures are a prerequisite for automation.'* He also reported: *'Even today, our product portfolio is by far not complete. Our current strategy is to participate in tenders for a large array of different machine sizes and application types. Obviously, it takes more time to engineer a 'first-of-its-kind' since the number of engineering hours required decrease with experience. However, it helps us in broadening our knowledge and product base. If you have seen many different variants of a product, it becomes easier to develop modular product structures allowing a reuse of components for many different orders.'*

Level 3 – Automation of tendering (today)

In its third year of business, BETA introduced sales configurators to support an automated generation of tender documents. Most recently, the commercial product structures stored in the configurators were remodeled to allow cost calculations for different production stages instead of only the final turbomachine. As a manager of BETA explained: *'I believe the remodeling of the product structures considerably increased our data quality. The newly available data improves the accuracy and speed of the cost calculations that we execute in tendering.'*

Outlook

As a result of the standardization and automation, the management at BETA expects revenues to grow disproportionately to the number of people employed in the future. The management considers it key to further improve the product structures and extend the product portfolio. As a manager explained: *'If we manage to improve our product structures, the use of pre-engineered solutions will become feasible and we will be able to advance our level of design automation. Today, by far too many calculations have to be done for each order. A major advantage would be to have more design guidelines. They would avoid that calculations have to be repeated for every order to confirm the feasibility of the design.'*

Company GAMMA

GAMMA is a construction equipment producer that participated in the case study with its division developing and producing asphalt mixing plants. In recent years, the division expanded its global operations by opening new development and production sites abroad. In 2014, the company sold 200 asphalt mixing plants, each requiring 1,400 hours of order-specific engineering on average.

Level 1 – Ultimate freedom

Initially, processes were only roughly defined and bill-of-materials were often incomplete or not fully specified. Tenders and orders were handled according to the understanding and knowledge of individuals. A product manager of the division described the level of automation at that time as follows: *'I believe that automation only happened in the mind of people. Some of us automated processes for ourselves.'*

Level 2 – Product standardization

In 2009, GAMMA launched 'Project Optima', which aimed at reducing costs and lead times. The reductions were to be achieved by a concise definition of the technical product structure, accompanied by a guideline explaining how the new product structure was to be used. As a manager explained: *'As a result of Optima it wasn't possible to order parts by simply describing them anymore. Instead, material numbers had to be specified. Before Optima our engineering had to confirm every single order. Optima achieved that orders not requiring special parts could go straight into work preparation.'*

Level 3 – Automation of tendering (today)

GAMMA uses sales configurators for the generation of tender documents. However, the commercial product structures stored in the sales configurators are not coherently linked with the technical product structures stored in the ERP system and used for order execution. To date, no interface between the two systems exists. Component groups are manually copied into the ERP system after an order has been won. Custom-built software for the configuration of core parts is scattered throughout the engineering department. Since most of the solutions are complex and require a certain expertise, the tool developers and their close peers primarily use them.

Outlook

In its quest for global market presence, GAMMA seeks to advance its current level of standardization and automation to improve operations efficiency. A major challenge related this aspect is the fact that the division conducts the order-specific engineering at five different locations and that each location stores their order-specific solutions locally. In the past, the engineering sites in China and India have already worked on highly similar order-specific solutions simultaneously and only realized this after project end. Company representatives unanimously expressed that they regard further automation of order execution as the next step. At time of the investigation, the division faced the challenge of identifying the product families for which automation promised the highest savings.

Company DELTA

DELTA participated in the case study with its division delivering high-rise elevators. The division, which designs and produces elevators for particularly high and often extremely challenging buildings, is known for its innovativeness and strong global market presence. In 2014, the division sold 2,000 elevators, each requiring eleven hours of order-specific engineering on average. In merely requiring eleven hours of order-specific engineering on average, elevators are not the most extreme type of ETO (see Willner et al. [22] for an analysis of different ETO types).

Level 1 – Ultimate freedom

Until the early 1990s, DELTA engineered every high-rise elevator basically from scratch. As a director pointed out: *‘At that time, every single order required engineering. We had not yet discussed which components could be pre-engineered and which should be engineered-to-order. We simply accepted orders the way they came in.’* The division hardly used supporting IT systems for tendering and order execution, and processes were only roughly defined.

Level 2 – Product standardization

Faced with growing competition, the management at DELTA came to realize that customers regarded their products as very expensive and the delivery times as too long. A manager of DELTA stated: *’That is why we defined our first product lines. We started with the very top segments and then slowly worked our way down. Initially, product lines were noted down on paper. We also defined index price lists.’*

Level 3 – Automation of tendering

In 2005, DELTA introduced the first sales configurators to speed up tendering. A manager of DELTA emphasized: '*The introduction of sales configurators led to new processes and the organization required restructuring. For example, we split up the responsibilities between new product development and order-specific engineering. Further, we pushed sales to sell the pre-engineered solutions specified in the configurator.'* The manager also expressed: *'Sales configurators helped collect and prepare data that helped us decide what else we could standardize. Another advantage of the configurator was that everybody started doing everything right or wrong in the exact same way.'*

Level 4 – Automation of order execution (today)

In the next step, it was decided that product specifications should no longer be copied manually from tendering documents after an order had been won. Instead, the configurators, originally conceived for the generation of tendering documents were to be extended for use in order execution. Parameters selected within tendering were to be used to automatically generate engineering drawings and purchase orders later on. Just the special components not included in the fixed solution space should be calculated and designed manually by the department in charge of order-specific engineering. Additionally, a database for storing order-specific engineering requests with search functions allowing the retrieval and reuse of engineering solutions from previous projects was introduced. As a director expressed when discussing the changes: '*Processes had to be redesigned again, and calculation rules had to be validated. In the beginning, it was difficult for some of our engineers to trust in the automated order process. Previously, our engineers had calculated safety margins based on their individual experiences. Now, we had intense debates if the tolerances and rules proposed by the systems were correct.'*

Outlook

DELTA does not intend to advance its current level of design automation in the future. The division considers the capability to deliver products that are partly engineered to customer specifications as a core order winner. A new release of the configurators expected to go-live in 2017 primarily targets performance improvements and a simplification of the solution space.

Figure 3 illustrates the design automation paths of the four case companies with the key milestones.

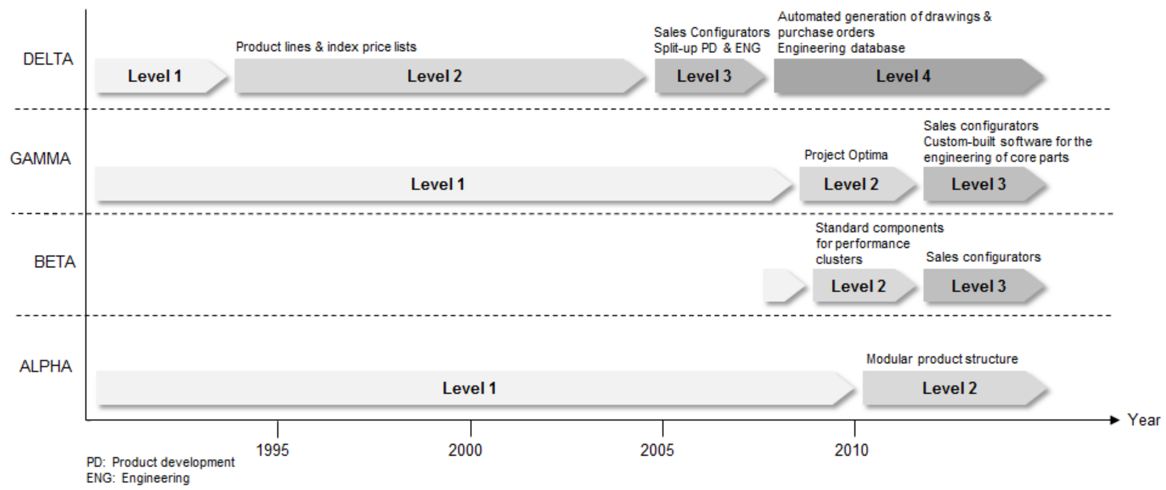

Figure 3: Design automation paths of case companies

4.3 Model validation

Model validation was based on two focus group workshops and a self-assessment. The participants of all three validation rounds generally confirmed the selected levels and dimensions and agreed upon the proposed design automation paths.

We gained the following insights from the focus group workshops. First, workshop participants at EPSILON expressed doubts that the tendering phase necessarily has to be automated before automation of the order execution can take place. We came to the conclusion that certain engineering subtasks (e.g. related to particular modules or components) can be automated without having automated tendering but not the full order execution. Therefore, we slightly altered the wording used to describe level 3 and 4 in the model. Second, workshop participants at ZETA proposed to incorporate industry-specific factors as stage indicators in the model. While we generally agree that this might increase the usefulness of the model for managers, we regard an elaboration of this issue as out of scope for our research question. When discussing the maturity models at the focus group workshops, it also emerged that managers should not necessarily attempt to advance all their products to Level 5, in which case they would become MTO products. In line with Willner et al. [22], we argue that it depends on the product type which degree of design automation is most appropriate.

As part of the self-assessment, the Engineering Director at ETA noted: *'I consider my division to be currently located at level 2 aiming towards moving on to level 3. In that respect, I regard it as a major obstacle that the information and knowledge gathered in previous projects is primarily accessible to the engineers having been involved in the specific projects. Formalized knowledge sharing processes and systems are not yet fully developed in our company.'*

Our study participants unanimously confirmed that the model delivers meaningful and applicable insights. A participant expressed that he intends use to the maturity model to discuss the next steps required for automation with the upper management. The managing director of one of the validation partners intends to apply the model in design automation projects at customer sites.

4.4 Summary and discussion

Figure 4 presents the maturity model that we derived from within-case analysis combined with cross-case comparisons. It comprises five distinct maturity levels (*ultimate freedom*, *product standardization*, *automation of tendering*, *automation of order execution*, *full automation*) that are delimited by the criteria that a change of activities has taken place through all four dimensions (e.g. an overall level 3 is achieved only when a level 3 or higher is achieved across all four dimensions). We used a bottom-up approach for developing the distinct maturity levels in determining the required activities first and then recorded the appropriate names that reflect these. According to De Bruin et al. [63] such a bottom-up approach should be used for the development of maturity models in more established domains.

	Level 1 – *Ultimate Freedom* –	**Level 2** – *Product Standardization* –	**Level 3** – *Automation of Tendering* –	**Level 4** – *Automation of Order Execution* –	**Level 5** – *Full Automation* –
Strategies	• Open solution space; customer is free in defining order specifications • No performance management: budget and schedule are not tracked and often exceeded	• Definition of product lines; creation of product structures; product modularization • Distinction between standard, configurable and special components • Basic performance management: budget and schedule are manually tracked	• Implementation of commercial product structures in sales configurators → formalization of solution space • Advanced performance management: budget and schedule are tracked; deviations are monitored	• Implementation of technical product structures in engineering configurators → formalization of solution space • Superior performance management: Budget and schedule are tracked; deviations are monitored and used to define improvement measures	• Fixed solution space that is regularly adjusted to customer needs • Performance measurement used for continuous improvements
Processes	• Ad-hoc processes, occasionally chaotic	• Nascent processes; no clear distinction between processes for standard, configurable and special components • Replication of processes across locations	• Process 1 (standard & configurable components): Tendering guided by sales configurators; automated generation of tender documents (semi-automation) • Process 2 (special components): roughly defined process	• Process 1: Order execution process guided by engineering configurators; automated generation of purchase orders & drawings • Process 2: meta-process for special components	• Fully defined and coordinated processes
Systems	• No IT systems for tendering and order execution exist • Data is collected randomly	• Product structures are stored in various IT applications (e.g. PDM systems, ERP and spreadsheet applications) • Structured, but manual data collection	• Sales configurators are used • Configurators support standardized and automated data collection within tendering	• Engineering configurators and order-specific engineering databases are used • Interfaces between configurators and CAD systems are set up • Configurators support standardized and automated data collection within order-execution; data used for product optimizations	• Fully integrated IT systems for tendering and order execution in place • Rigorous and automated data collection and analysis
People	• No clear roles and responsibilities • Success depends on individual effort and heroics	• Development of skills on the individual level	• Formation of groups and specialization (split up between people who define the MTO process, who execute the MTO process and people who improvise the ETO)	• Routines for standard & configurable components (first plan, then execute); automatic execution • Routinized improvisation for special components (simultaneous planning and execution)	• Clearly defined roles and responsibilities • Success depends on collective effort and comprehensive integration of tasks and roles

MTO

Figure 4: Maturity model for design automation

Along the *strategies dimension,* the four cases supported us in identifying the steps required to develop a solution space promoting design automation. In that context, our case studies brought to light that mature product structures are an important prerequisite for successful design automation. Companies have to distinguish between standard, configurable, and special components to reach level 2 in this dimension. Advancing to level 3 and 4 entails formalizing the solution space through the implementation of product structures in configurators. Level 5 requires a fixed solution space, meaning that a product is fully configurable and does not contain any special components.

Along the *processes dimension*, we observed that processes evolve together with strategies and systems. In level 2, companies start to develop nascent processes and replicate these across locations. Distinct processes for standard/configurable and special components are required for advancing to level 3. Processes for standard/configurable components are fully defined in level 4 while meta-processes (higher-order processes used to construct other processes [71]) exist for special components. In our view, the concept of the meta-process is closely linked to the ETO-enabling process introduced in Schönsleben [24] and based on the capability of *routinized improvisation* (see *people dimension*). In level 5, all processes are fully defined and coordinated.

Along the *systems dimension*, the case studies helped to determine which IT systems to implement in which order for design automation. In level 2, product structures are stored in a large variety of IT applications, which are not necessarily suitable for handling complex and hierarchical product structures coherently. Beyond serving as data repositories for both part numbers as well as bill-of-materials, PDM/PLM systems do not play a big role in the sales-delivery process of our case companies. Some of them use PLM systems in product development but we could not identify a single case where a PLM system is used as leading system along the entire product lifecycle. In level 3 and 4, configurators with interfaces to CAD systems are implemented to enable the automation of repetitive design tasks for standard/configurable components. Correspondingly, we noticed that engineering databases are set up to facilitate the reuse of special components and order-specific solutions. Contrary to the common notion that design automation is mainly applicable for repetitive design tasks (e.g. [7,13,16]), the cases studies demonstrated that creative design tasks can also benefit from design automation. Company representatives at DELTA reported how their engineers deliberately retrieve former projects stored in an engineering database and use them as inspiration for creating new order-specific solutions. In level 5, fully integrated IT systems for tendering and order execution are in place.

Along the *people dimension*, we found that the required skill sets and behaviors of people change with automation. While success initially depends on individual skills and 'heroic' performance, the importance of collective effort and a comprehensive integration of tasks and roles later on gains momentum. As demonstrated by the cases, moving to level 3 requires the formation of groups and specialization. The empirical cases demonstrates how it is distinguished between the people in charge of developing the solution space and defining the

MTO process (called *product line management* at *ALPHA),* the ones handling the order execution (called *work preparation* at BETA), and the ones who improvise the ETO (called *application engineering* at ALPHA). In level 4, emergent routines (defined by Nelson and Winter [72] as patterns of action that store tacit knowledge and function as *organizational memory*) contribute to automated order execution for standard/configurable components. We use the term *routinized improvisation* (defined by Tan [73] as repeated improvisation that entails simultaneous planning and execution) to describe how special components, which are often characterized by a high degree of novelty and complexity, are handled efficiently and consistently.

5. Conclusion

This paper proposes a maturity model as a framework for analyzing and improving design automation activities in ETO companies. Through integrating evidence from literature, case studies, and focus group workshops, we identified five distinct maturity stages across the dimensions strategies, processes, systems and people. Empirical cases gave insight in the activities happening at the different stages and allowed us to describe them in detail.

Our investigation makes a number of contributions to the literature. First, we bring together several literature streams, which have formerly been disconnected, in investigating design automation in the ETO sector from a maturity perspective. Beyond that, we extend the extant literature on design automation by providing a framework that takes organizational and managerial aspects into account. Second, our cases revealed that design automation is not exclusively applicable to repetitive design tasks but also supports creative tasks. Through identifying this additional opportunity for design automation, we augment previous research in our field. Third, we adopted the concepts of routines and routinized improvisation from the field of organizational studies to understand how tacit knowledge can be incorporated in ETO processes. We believe that additional studies applying these concepts on the operational challenges of the ETO sector might yield promising results.

Managers can apply the model as a guideline on how to approach design automation in sales-delivery processes. This should help them reduce the time and effort required for design-related tasks leading to competitive advantage. We argue that the model also supports the assessment of design automation opportunities. In its current form, managers can use the model to determine where they stand today and what the next steps should be. As the validation rounds brought up, future research could seek to develop stage indicators that help assess which degree of design automation should ultimately be targeted in a particular line of business.

This study has only begun to explore the organizational and managerial requirements of design automation in the ETO sector. The maturity model for design automation was developed with cases from the mechanical engineering industry. Future investigations may wish to assess the applicability of the model in a broader range of industries and identify industry-specific adaptions the model might require. For example, we believe that an application in the construction industry might make a particularly interesting case allowing a comparison of the similarities in requirements between design automation and building information modelling.

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Appendix A. Interview guideline

1. General information
   1.1 Interviewee information (name, position, in the position since when)
   1.2 Division information (name, main products, # employees, annual revenue)
2. Engineer-to-order
   2.1 How does your division define ETO?
   2.2 Name the different ETO products of your division. Estimate how many units of each product are sold annually and how many order-specific engineering hours are required per unit on the average.
   2.3 Describe the ETO processes of your division (product development, sales, customer-specific engineering, production & logistics, delivery). Which departments are involved in each of the process phases?
   2.4 How do you expect your share of ETO products to develop within the next 10 years?
3. Design Automation
   3.1 What does a standardization and automation of design processes imply for your division?
   3.2 What are the main drivers for design automation in your division?
   3.3 Does your division attempt to achieve different degrees of automation for different types of ETO products? If this is the case, which criteria do you apply to decide to which degree to automate for which product type?
   3.4 Please describe the current status of design automation in your division. Which elements of your design processes are automated?
   3.5 Describe the pathway of your design automation along the dimensions ‘strategies’, ‘processes’, ‘systems’ and ‘people’.
   3.6 Which data did you require for design automation?
   3.7 How far are your product structures currently developed?

3.8 Which challenges did you encounter during design automation?
3.9 What is the intended future design automation path of your division?