Lecture Notes in Production Engineering

Thomas D. Brunoe
Kjeld Nielsen
Kaj A. Joergensen
Stig B. Taps *Editors*

Proceedings of the 7th World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2014), Aalborg, Denmark, February 4th - 7th, 2014

Twenty Years of Mass Customization – Towards New Frontiers

MCPC 2014

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Preface

The first MCPC conference was hosted by Hong Kong University of Science and Technology in 2001. Since then the MCPC conference has grown to become the primary conference for presenting and discussing current issues and recent developments within the fields of Mass Customization, Personalization, and Customer Co-Creation. Since 2001, the conference has been hosted by University of Technology Munich (2003), Hong Kong University of Science and Technology (2005), M.I.T. (2007), Aalto University (2009), and UC Berkeley (2011). The 2014 MCPC conference, the seventh in the series, for which the contributions are presented in this book, is hosted by Aalborg University.

The MCPC 2014 is a multi-track conference featuring a combination of high profile keynotes with expert talks, panel discussions, paper sessions, workshops, receptions, and much more. While it is devoted to sharing and discussing the latest research in the field, the MCPC conference has a strong focus on real-life applications. Since its beginning, the MCPC conference has had an equal share of participants, practitioners, and academics/researchers. This makes the MCPC conference truly unique among many conferences. It strives to connect MCPC thinkers, first movers, entrepreneurs, technology developers, and researchers with people applying these strategies in practice.

Twenty years ago Mass Customization was acknowledged as the "New Frontier in Business Competition". Ever since, the industry has been applying the concept and researchers have developed the topic into a well-established research area and businesses have formed new strategies. More knowledge, methods, and technologies are available now than ever before. Along with general Mass Customization topics, this conference addresses Mass Customization from a historical perspective, looking at both mass customization in the past 20 years and toward the new frontiers in the 20 years to come.

The MCPC 2014 conference wants to engage academics, business leaders, and consultants in fundamental debates through a set of plenary presentations, workshops, discussion panels, and paper presentations. Continuing our tradition, we invite contributions from a wide range of specialists. MCPC 2014 is looking for contributions in cutting-edge research, as well as insightful advances into industrial practice in key areas.

This book presents the latest research from the worldwide MCPC community bringing together the new thoughts and results from various disciplines within the topics:

- 20 Years of Mass Customization—Reflections
- Choice Navigation
- Product Modeling
- Solution Space Development
- Manufacturing Systems for MCPC
- MCPC Applications
- Open Innovation

All papers presented in this book have been peer reviewed prior to publication to ensure the same high quality as seen on previous MCPC conferences.

The organizing committee would like to thank the MCPC community for the support for this conference, hoping that all participants, academic and industrial, will benefit from the presentations and discussions.

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MCPC 2014
twenty years of mass customization – towards new frontiers

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Contents

A Bonded Experience: "Value Creation as the Creation of an Experience, Within a Business Relationship"

Ron J. A. Journée and Marcel E. A. Weber

Abstract In this paper, we investigate the application of the concepts of customer experience (CX) and co-creation for SMEs in the B2B sector. Based on a systematic review of extant research on the subject of CX, we will recognize that customer experience management (CXM) can be a new way for organizations to create a competitive advantage, simultaneously creating more value for their customers. We will introduce a conceptual framework for a better understanding of the concept, identifying several elements that have to be taken into account in CXM, i.e., the types, levels, and strengths of experience; the tacit and measurable outcomes of a great CX for the firm; the methods to measure CX; the conditions to execute CXM; the possibilities for CXM by the firm, such as the management of experience providers and the application of the customer journey approach to gain insights into customers' experience; and, finally, the role that customers have in CXM. With this latter element of our framework, we will be able to cross the bridge from CX to customer co-creation, in particular the co-creation of experiences in NPD. Reflecting these insights on SME practice will teach us what small- and medium-sized enterprises can do to apply CXM. In that respect, we will observe that research has not reached a sufficient level of knowledge to aid firms in achieving this goal. We intend to further investigate the application of CX concepts in SME in ongoing studies.

Keywords Customer experience management · Customer co-creation · Open innovation · B2B

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1 Introduction

Customer co-creation has become an important and novel way for firms to practice open innovation in creating new products and services (NPD/NSD) [1]. Co-creation is however not limited to NPD/NSD, but can be used to create new CXs as well [2]. The concepts of value co-creation and experience management have entered the domain of marketing management [3]. Traditional marketing views customers as rational deciders with mainly attention for functional product properties and benefits. Experiential marketing, on the other hand, perceives customers as both rational and emotional beings that are looking for positive experiences [4]. Research in the past decade demonstrates that the traditional point of view has not changed much, in spite of increasing customer satisfaction surveys. A satisfied customer is not a guarantee for loyalty, extra turnover, or a larger market share. To increase loyalty and customer advocacy, companies have to consider delivering a positive CX. In order to provide a positive CX, it is also recommended to co-create with customers [2]. Companies will profit if this is done in a proper way.

In spite of these positive insights about CX, academic research on the subject of CX in B2B SME is limited. CX seems to be an exclusive topic for practitioners in practice-oriented literature, e.g., Shaw and Ivens [5]. These publications tend to focus on the practical managerial aspects of CX, instead of developing and researching theory on the antecedents and consequences of CX. For those cases where theory has been developed, e.g., Schmitt [6], theory seems to be aimed on large, multinational companies operating in the B2C. Academic research intended to study the subject for the benefit of the SME, particularly in the B2B, seems to lack.

In this paper, we try to start the debate on the advantages and disadvantages of customer experience management (CXM) for the SME by providing an overview, based on systematic research of the literature. In order to do this, we will first investigate the ontology of CX. Next, we develop a conceptual framework that covers all important aspects of customer experience (CX) and co-creation in seven interrelated elements, entailing constituents, moderators, outcomes and measurements of CX and co-creation, as well as conditions, business interactions, and customer actions to improve or create CX and co-creation. At this stage, we cross the bridge from CX to customer co-creation. In the end, we will reflect on this body of knowledge, contemplating on its use for the SME.

2 Ontology of (Customer) Experience

Experience is a main construct in the phenomenological philosophy [7]. The phenomenology regards human beings as a subject that undergoes perceptions, interpretations, and experiences, where experiences represent a more complex concept than the meaning in ordinary language. Experience is the concrete existence of man "as being in the world" [7] and is essentially a matter of "meaning-making" and thus a question to be addressed by interpretive approaches [8]. This viewpoint has been adopted in social psychology as well, for instance, in the works of Kurt Lewin who postulates that social behavior is determined by subjective interpretations of events in the environment [9]. Experience is not tacit and concrete, but refers to the qualification of one's subjective perceptions and therefore personal [10]. Experience can manifest itself in many ways, such as physical, mental or thoughts, emotional, spiritual or religious, and even virtual [11].

The role and importance of experience in consumption and use of goods and services was first proposed by Holbrook and Hirschman [12], who introduced CX as an addendum for the contemporary consumer behavior models that were mainly based on rational behavior of consumers. Based on this insight, Schmitt advises "to treat consumers as living human beings with experiential needs rather than as rational price- and attribute-driven information [6]." Consumers want to experience that their feeling, senses, and soul are being "touched" and are in search of authentic and honest treatments by providers. Consumption is no longer a matter for "customers" in the depersonalized sense, but holistic for individuals [6]. According to Pine and Gilmore [13], experiences occur when customers are being involved in such a way that it provides a permanent and unforgettable impression. The experience is memorable and personal, touching the customer on an emotional, physical, intellectual, and even spiritual level [13].

3 Experiential Marketing: Customer Experience in Marketing

As observed earlier, Holbrook and Hirschman first introduced CX in marketing science in 1982 as an expansion of the existing, rational behavior models with experience aspects. It is in the late 1990s that more attention for the phenomenon is given by scholars in publications, e.g., Pine and Gilmore [13], and Schmitt [14]. Pine and Gilmore were the first in describing the influences of experience in terms of the economic added value for customer and firm. They prophesized that, after commodities, products, and, subsequently, services, experiences are the new economic offering, with in the end, the transformation [15]. These publications were the cause of a paradigm shift from organizations aiming to provide the best product or service, to organizations that have the aspiration of providing what customers experience as the most pleasant in their relation, which, aside from the moments of consumption, consists of several moments of interaction between customer and provider. Contact and interaction moments, or touch points, are crucial for the experience the customer gets [5]. Most of these publications focused on creating a hedonic CX, where fun, joy, and excitement are the emotions to be triggered. Subjective experiences, however, do not only consist of hedonic elements. Experiences can also entail irrational aspects, leading to irrational behavior [16].

3.1 Development of the Concept

Following Pine and Gilmore, more and more attention has been given to CXM as a new paradigm in marketing theory in the past decade. CXM is now regarded as a new lever to create value for customers as well as for companies [4, 5, 17–22]. CX is the result of all interaction a customer has with a product or service provider.

With the advance of technological, socializing, and globalizing trends, companies can get closer to their customers. Firms and customers nowadays focus on collaboration in networks in order to respond quickly to changing needs and to focus on what they are good at. In that respect, customers will look for more meaningful experiences, so they can shape their own existence. In a society where self-actualization and welfare become central, firms will have to focus on guiding customers in achieving this by providing meaningful and memorable experiences that create transformations in people's lives. To facilitate this, firms need to create a platform where customers and firms can jointly create a context for giving more sense and meaning to one's life [21]. The dialog between firm and individual customer is the foundation for the co-creation of personalized value [23].

3.2 Current Status: Customer Experience Management

It is not surprising that CXM in marketing is gaining attention. CXM is proposed as the new way to get insight into customers' preferences and needs, which influence behavior and loyalty [17]. Firms realize that relationship based on experiences will aid in the attraction and retention of customers [13, 24]. CXM is now regarded as a way to distinguish the firm from its competitors and to create more value for customers and firms' stakeholders; it has become essential to survive in present competitive environments.

4 A Conceptual Framework for Customer Experience Management

We have systematically reviewed the extant literature on CX and CXM, in order to identify the necessary elements for our conceptual model. We refer to references for an overview of the reviewed literature. The resulting framework is depicted in Fig. 1.

Our first observation is that CX consists of several constituents (box "Constituents," depending on the point of viewing at the concept, which can be classified as types, levels, and strength of CX. Achieving a certain intended type, level, and strength of CX can lead to desired outcomes (box "Outcomes") for the firm. As we will see, these outcomes can also be classified in material or financial

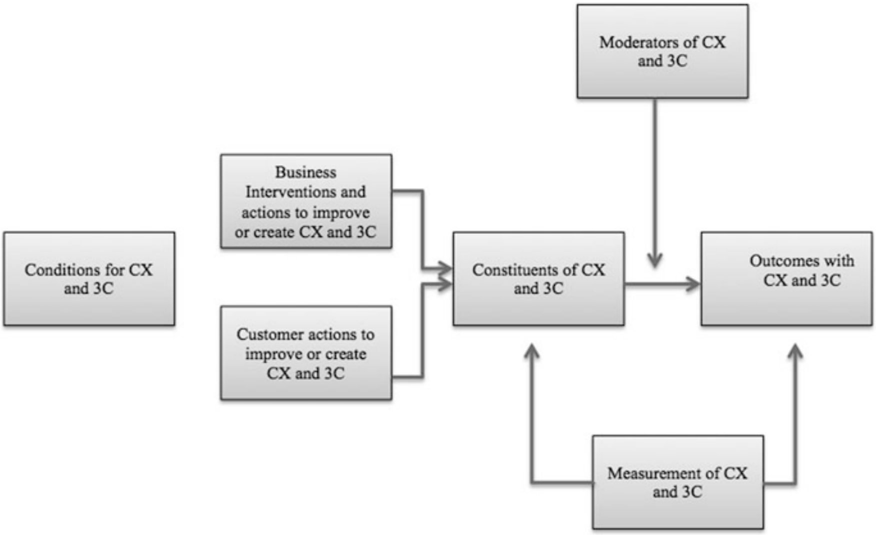

Fig. 1 Conceptual framework for customer experience management (CX)

outcomes, and immaterial outcomes. To achieve the intended CX, companies can take some actions (box "Business Interventions and Actions"), both internal and external, influence customer behavior (box "Customer Actions"), but can also depend on some external influences (box "Moderators"). To complete the management cycle, so we can truly speak of CXM, companies need to measure the realized CX (box "Measurement"). We will now review each box or element of our conceptual model referring to insights from CX and CXM literature in the following subsections, where, at a certain point, we can also provide a definition for CX.

4.1 *Constituents of Customer Experience: A Taxonomy*

According to Meyer and Schwager [25], experience is a personal and subjective response that customers have in direct or indirect contact with an organization. As has been argued before, CX does not only entail cognitive, functional, and rational aspects of customer behavior, but the emotional and irrational aspects as well [4, 20]. Several scholars, e.g., Gentile et al. [17] and Schmitt [14], attempt to classify the construct of CX in types. Schmitt [14] provides us with a comprehensive set of types, for which we will use the anagram FASTR as taxonomy:

- Feel, referring to the emotions and feelings in the experience;
- Act, referring to physical experience and behavior;

- Sense, when it comes to the sensory experiences as smell, taste, sound, and touch;
- Think for rational, intellectual, and cognitive experiences; and
- Relate, referring to social identity, relational experiences resulting from relations with a (peer) group, culture, or lifestyle.

Experience can also vary in strength; although both excited, two persons can experience this excitement at a different intensity. The ultimate, superior experience is the so-called "flow" [26]. CX is also no longer considered a mere hedonic aspiration of customers, as proposed by several scholars [12, 18, 19].

Experience can be manifested at several levels of the contact [27], where there is a distinction between brand level, transactional level, and relational level. Other levels mentioned in the literature are the customer journey [28], the individual interaction, and the total CX [28, 29]. We now propose the following classification for the levels of CX:

1. Interactional experience level, referring to the experience for each individual interaction between organization and customer. This experience can vary in strength, direction, and quality, depending on how the interaction is shaped and executed. For example, a customer can be very pleased when buying a product in the store, but the experience can turn into disappointment when he tries to use the product.
2. Relational experience level, when it comes to the experience one gets from interacting or communicating with certain individuals or departments of an organization. We can start to like the shop attendant, while hating the customer service whenever we call for help.
3. Channel or transactional experience level, where experience differences can occur, depending on the channel in use. We can have a different experience when buying something in the store compared to buying it online.
4. Customer journey experience level, which is a composition of the previous three experience levels when it comes to the customer journey.
5. Brand or organizational experience level where it comes to the experience that derives from contact with the virtual brand or organization. We can get a pleasant feeling when seeing the logo of Apple or feeling good when we read something about LEGO.
6. Total CX level, which covers the experience a certain person can get from all his contacts and touch points with an organization in his life.

The CX starts at the first contact and develops in strength, direction, and types on all following interactions, touch points, communication, etc. So, the FASTR components vary in time, depending on the type of interaction, but also shaping and reshaping the total CX. In that way, we cannot speak of CX as a static entity. CX is of a complex nature.

A definition for customer experience There is no consensus on the construct of CX. Based on our previous elaboration, we can, however, try to provide a definition for the concept, which we will use in our ongoing research.

> Customer experience is a personal and subjective response that customers have on direct or indirect contact with an organization, at several levels. By influencing this CX the organization tries to evoke several kinds of perceptions to a customer: emotional, physical, sensorial, rational en relational, where customers and the organization co-create unique, meaningful experiences in order to achieve a profitable, durable and affective relationship that gives value to all stakeholders.

4.2 The Outcomes of Customer Experience (Management)

Creating the ideal CX and brand experience will have a positive effect on a sustainable competitive advantage for the firm, reflected in long-term continuity and survival [30]. CX also has a positive effect on customer satisfaction and loyalty [6]. It has also been asserted that meaningful CXs create value for both customers and organizations [17, 21]. Vargo and Lusch [31] suggest that value is always unique and is determined by the beneficiary. In the sense that each individual can get a different experience from the same stimulus, this means that the valuation of a product or service can differ among customers. Value is, in that respect, a similar concept as experience: highly personal and subjective.

Minckiewicz et al. [32] review the academic debate on the concept of value and conclude that no consensus exists about the concept. They discover four different approaches for "value" in the marketing literature: (1) value in exchange; (2) value in use; (3) value in experience; and (4) value in context. Value in experience seems to fit the best in the CX philosophy and entails that the customer values a product or service as a function of his experience. In a market of value-in-experience, the market becomes a platform for conversations and interactions between customers, communities, and firms [21].

Summarizing, we can depict many possible outcomes from good CXs for the firm in two categories, see Table 1.

4.3 Conditions for Customer Experience Management

A basic condition to build customer loyalty is market and customer orientation: an external focus [33]. Market orientation leads to market- and customer-focused strategies and higher levels of customer satisfaction, leading to loyalty and long-lasting profitability [34].

4.4 Moderators of Customer Experience

Every organization creates a CX as a response, positive, neutral or negative, conscious or unconscious. The moments that experience becomes manifest are called touch points. In general, these touch points refer to interactions between an

Table 1 Outcomes of positive customer experience

Financial and measurable outcomes	Immaterial or organizational outcomes
• Increase in market share [17]	• Enhancement of customer relations [35]
• Increase in profitability and sales [30, 35]	• Recommendation and word of mouth [22]
• Increase in repeat sales [36]	• New market entry [37]
• Brand equity, brand loyalty, and customer equity [17]	• Firm image [30, 37]
• Customer satisfaction and loyalty [17, 30, 35]	• Reputation [38]
• Employee satisfaction [37]	• Long-lasting competitive advantage [28, 30]
• New customer attraction [37, 38]	• Competitive distinctiveness, ability to charge exclusive prices [13]

organization (or brand) and all of its stakeholders, including customers, employees, suppliers, etc. [39]. The success depends on how effective the organization is in CXM, but can also be influenced by other factors, which the organization cannot control. Usually, other customers and external stakeholders, such as local community, media, action groups, government, and public opinion, are accountable for this influence. The intensity of competition in the market is an important external factor, which influences CX [24]. The higher the competitive intensity is, the sooner that companies tend to look for a sustainable competitive advantage [17].

Organizations can try to influence the external factors, requiring specific actions to accomplish this, which we will not elaborate on, except for those that are identified as important moderators of CX.

Shaw [40] identifies another important external factor: customers' expectations. Customers shape their expectations based on previous (life) experiences, including "traits", "life events", and other influences [40]. From these "pre-experiences", customers develop attitudes that shape their expectations [41]. It is important for organizations to know and manage these expectations and forthcoming needs of their customers, since they influence the experience [42].

4.5 Measuring Customer Experience

Several studies [43] demonstrate that the CX the firm thinks it delivers is estimated higher than what customers think. It is therefore necessary to measure CX in order to evaluate the efficacy of the CXM. But it looks as if the appropriate methods to measure CX do not exist. That is probably why CX is often measured through customer satisfaction surveys. Customer satisfaction in itself is a poor predictor for a firm's quality, since satisfaction can be high, while growth and loyalty remain low [44]. An important critique on the measurement of customer satisfaction is that customer satisfaction often is defined on firm-established criteria, without examining what truly moves the customer. Another often used method for the measurement of CX is the Forrester Customer Experience Index or CXi [45]. With this method, customers are asked three main questions: How well the organization met their needs, how easy it was to get things done, and how pleasant the collaboration has been; the CXi is then an average of the score for these three questions.

Customer loyalty can be measured through the Net Promoter Score (NPS) [44]. Through the NPS, an organization identifies its customers in three categories: promoters, detractors, and passives. The method consists of one question to customers, the ultimate question, stating "Would you recommend this organization to friends, colleagues or acquaintances [44]?" Customers that tend to recommend (promoters) are usually loyal to the organization.

A recently developed measurement for CX is the Dutch Performance Index (DCPI), which measures value-to-customers (V2C) and value-to-firm (V2F) [46]. The advantage of the DCPI over other methods of measurement is its measurement of more customer-focused indicators, leading to a more complete picture of CX in organizations. To measure experience in online situations, a model with corresponding constructs has been developed [47], based on flow [26].

We observe that none of the aforementioned methods is aimed at measuring what customers truly feel, their emotions. Customers are merely asked to reflect on their experience to evaluate this in a cognitive mode. The affective and sensorial character of CX requires a method that is capable of evoking perceptions and emotions [48], which is not an easy affair, because emotions are interpretative, contextual, and almost untouchable [49]. Looking into the psychological discipline to find the appropriate measurement methods for emotions in consumption situations does not seem to give any help, either [50]. We observe that the marketing discipline still lacks a comprehensive, quantitative method of measuring emotions in CXs. Arnould and Epp [51] and Palmer [52] argue that, because of the subjectivity of experience, qualitative methods are better suited to study CX.

4.6 Customer Experience Management: The Actions from the Firm

To meet the emotions from customers, the organization is required to be capable of delivering a total CX through effective communication and empathy. CX should be managed [5]. All classic marketing mix actions are therefore at an organization's disposal, but now with a focus on CX. For instance, customer segmentation is nowadays based on experience [53]; the multi-channel approach of firms should be focused on enhancing CX [54]. However, firms should not only focus on functional and operational factors to manage experience; organizational culture is also important in the sense that customers interact with employees, shaping their brand experience [55]. A positive employee experience has a positive effect on marketing, CRM, HRM, and the innovation strength of the organization [56]. It is not only the marketer's responsibility to manage CX, it is everyone's responsibility [57].

Experience providers Organizations can undertake some actions to manage their customers' experience [4, 5]. To do this, organizations can implement and manage the so-called experience providers, such as communication, visual and verbal identity, product presence, social media, etc. [4]. Berry et al. [28] suggest that organizations should have an eye for all "clues" that customers can detect in a transaction process. Experience providers and clues have to be managed in detail and should be used in their fullest potential to create great CX [4]. Attention has to be given to the spatial environment, the influence of other customers, waiting lines, sounds, visual expressions, and even the weather [24].

Customer journey management To analyze the experiential world of the customer, the customer journey approach has been developed [58]. The customer journey approach entails a description of all experiences a customer is exposed to, from long before the transaction takes place to long after this moment, depicting all touch points the customer has with the organization and other stakeholders during that time. The experience during this journey depends on expectations and the interactions the customer has. Some of these touch points are considered "moments of truth" since these moments are crucial and of high impact in creating a meaningful and intended CX [59]. To construct a customer journey, it is not only important to map what people say, but also how they feel and how they behave. An organization can deploy a variety of methods and techniques to elicit these insights, such as depth interviews, ethnography, observation, cultural probes, etc. [60]. In managing the moments of truth, organizations should consider the peak–end rule [61], depicting that experiences are evaluated on the peak and the end experience, and not on what happens in between. The peak or end experience can be either positive or negative, determining the strength and direction of the total experience. The other experiences are not really forgotten, but left out of the evaluation [62].

4.7 The Role of the Customer, an Active One

Experience management literature focuses substantially on the firm's role in experience management, e.g., Carbone and Haeckel [63]. But customers should also be prepared to create or co-produce their own experiences [29]. The customer has to provide inputs such as time, money, search actions, involvement, and personality [12]. Co-production of experiences creates value for the customer, such as time-saving, ease, and enabling a customer-specific, positive, and memorable experience [64]. But co-creation of experiences also creates value for the organization [2].

Therefore, literature also gives attention to how organizations can engage with the customers and address customers' capabilities to co-create [65], how to motivate them to execute tasks [66], and how to increase self-efficacy and self-confidence of customers [67].

4.8 From Customer Experience Management to Co-creation of Experiences in Open Innovations

Customer co-creation has become an important and novel way for firms to practice open innovation in creating NPD/NSD [1]. Co-creation is however not limited to NPD/NSD, but can be used to create new CXs as well [2, 35]. Carú and Cova [19] distinguish a continuum with at the one end experiences that are traditionally created by firms for their customers and, at the other end, experiences that are solely created by customers. They observe that, with the progress of time, firms tend to move from the one end to the other, passing through a co-creation stage, in which the firm provides the customer with the basic platform and raw materials, which are then being used by the customer, to mold and obtain his own experience. Each customer designs his own experience in the unique context of each interaction they have with the company. More important is the customer process and how he engages with the organization. When companies let their customer-facing processes co-evolve with customer processes, they inevitably find that the CX improves (and so does the experience of the customer-facing employees) [68]. Co-creation of experiences seems to become an important condition for services [69] and new product development [70], where firms no longer provide experiences, but provide artifacts, content, and platforms where customers can create their own, unique experiences [21].

New product and new service development become more and more focused on creating a total CX [58]. With NPD, apparently complex-looking problems can be solved in a relative simple way, by responding to users' experiences. It no longer is important how things look, but how they are perceived and experienced. Prahalad and Ramaswamy [71] already attended us on the increasing role of customers in the development of new products, services, and experiences. They emphasized to co-create value. This point of view has been adopted in later studies [72, 73] that acknowledge the trend that customers become more active in NPD and NSD. Customers seem to have a preference for firms that involve their customers in the creation and selection of their new products [38], leading to an increase in customer satisfaction, loyalty, and word of mouth, resulting in reduction in marketing costs [74].

5 Customer Experience and Co-creation Management in SME in B2B

SMEs usually constitute the majority of organizations in a society or economy. So, it is somewhat surprising to see that the larger part of CXM practice and research is aimed at larger enterprises, and in most cases at B2C companies. But, as we can observe as a result from our previous systematic research, we believe that theory on CXM is applicable for SME as well. SMEs, B2B companies in particular, are also dependent on customer loyalty and satisfaction. Loyalty and satisfaction can be enhanced with CXM.

Hollyoake [75] investigated the difference between B2B and B2C experience. He states that much of the current "wisdom" about CX relates to the B2C domain, which is because the largest budgets are within the B2C sector. Throughout B2B-experience, there is limited genuine hard evidence-based research and correlation to academic theory. Within the B2B sector, the absolute number of customer relationships may be fewer, but they are far more complex. They often include multiple contacts at differing levels across a large number of touch points. Customers themselves are becoming more vocal, sophisticated, and demanding around what they expect. Consolidation brings with it leverage and an ability to become more demanding of the supplier base. Hollyoake advises that, before embarking upon the pursuit of a bonded experience with every customer, it is important to understand the importance of the overall B2B relationship: The investment value input into the experience needs to match the level of value gained. In essence, an organization needs to segment its customers first and to be clear where and with whom to develop experience at the appropriate level. Once an organization has achieved the delivery of a consistent experience that meets base expectations, Hollyoake identifies key areas that enhance the B2B experience. These coalesce around co-creation of value, strategic understanding and contact at all levels across the organization, working within strategic business units, flexibility, and proactivity. Finally, the relationship moves into what is described as a "bonded experience." The four pillars of this bonded experience are trust, communication, interdependence, and integrity. It is not so much the relationship or the way customers are managed that differentiates an organization, but the experience developed through the relationship that makes the difference [75].

CXM can therefore also be of interest for SMEs [37], showing that it can increase profitability and market share, and attraction of new customers [24]. However, more research is needed to aid SMEs in B2B sectors to flesh out the specifics of the appropriate CXM for these companies.

6 Conclusion

Based on a systematic review of extant research on the subject of CX, we have recognized that CXM can be a new way for organizations to create a competitive advantage, simultaneously creating more value for their customers. We introduced a conceptual framework for a better understanding of the concept, identifying several elements that have to be taken into account in CXM, i.e., the types, levels, and strengths of experience; the tacit and measurable outcomes of a great CX for the firm; the methods to measure CX; the conditions to execute CXM; the possibilities for CXM by the firm, such as the management of experience providers and the application of the customer journey approach to gain insights in customers' experience; and, finally, the role that customers have in CXM. With this latter element of our framework, we have been able to cross the bridge from CX to customer co-creation, in particular the co-creation of experiences in NPD. Reflecting these insights on SME practice thought us that small- and medium-sized enterprises can also apply CXM, although they need to seek a trade-off with the cost of CXM. In that respect, we have observed that research has not reached a sufficient level of knowledge to aid firms in achieving this optimum. We intend to further investigate the application of CX concepts in SME in B2B in ongoing studies.

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A Case Investigation of Product Structure Complexity in Mass Customization Using a Data Mining Approach

Peter Nielsen, Thomas D. Brunoe and Kjeld Nielsen

Abstract This paper presents a data mining method for analyzing historical configuration data providing a number of opportunities for improving mass customization capabilities. The overall objective of this paper is to investigate how specific quantitative analyses, more specifically the association rule Apriori, can support the development within the three fundamental mass customization capabilities. The results of the Apriori analysis can be utilized for improving the configuration process by introducing soft constraints and consolidating the product structure by joining components or modules and finally for improving production planning and control.

Keywords Mass customization capabilities · Data mining product architecture · Apriori

1 Introduction

In any company, it is essential to offer products which match the needs and desires of customers to achieve sales and profit. This is true for mass producers as well as mass customizers; however, in mass customization, this issue is somewhat more complex than mass production due to a much higher variety and a more complex product structure. As pointed out by Salvador et al., mass customizers need three fundamental capabilities to be successful: (1) solution space development—identifying the attributes along which customer needs diverge, (2) robust process design—reusing or recombining existing organizational and value chain resources

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to fulfill a stream of differentiated customer needs, and (3) choice navigation—supporting customers in identifying their own solutions while minimizing complexity and the burden of choice [1, 2].

To support companies in developing their capabilities as mass customizers, some research has focused on assessing the fundamental capabilities, to evaluate within which areas the companies should strengthen their efforts. All three capabilities relate strongly to the product variety, which is also the main element which differentiates mass customization from other business strategies. This implies that tools and methods for continuously assessing, adjusting, and communicating the product variety are needed in order to improve the three capabilities. Mass customizers often utilize product configuration software for implementing a choice navigation process. A product configuration is a piece of software which allows customers or sales people to configure a product from a set of predefined variety. During a configuration process, a large amount of data are generated. These data can be utilized for different kinds of analyses with the purpose of improving performance within the three fundamental capabilities; Salvador et al. [3] address this specific as one of several approaches to achieve mass customizing capabilities. The data generated by a product configuration may include the following kind of data:

- Information about the customer
- Selected product options, e.g., parametric dimensions, optional modules, colors, and functional requirements.
- BOM information, i.e., specific components for manufacturing the product and quantities
- Sales process and manufacturing costs
- Lead times, quality data, etc.

The overall objective of this paper is to investigate how specific quantitative analyses, more specifically the association rule Apriori, can support the development within the three fundamental mass customization capabilities.

2 State of the Art

Data mining and association rules are a well-known field and have seen some application in the area of mass customization [4]. The data mining methods applied in this research have similarly been used in the domain of mass customization by among others: Geng et al. [5], Hong et al. [6], and Zhou et al. [7]. However, this paper contains two novel contributions compared with the current state of research. First, it presents a specific case study where the number of association rules is studied as a function of the support and confidence levels chosen. Second, it suggests a method to exploit this knowledge to choose (in the specific case) a reasonable combination of the complexity of association rules and support and confidence levels.

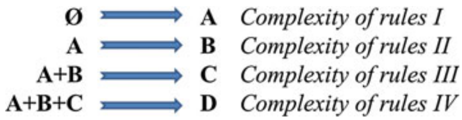

Fig. 1 An illustration of the complexity of the mining rules and their definition in this paper

3 Method

The paper uses the association rule Apriori, which is a widely used data mining rule [8]. The Apriori association rule is based on determining two parameters: confidence and support. Support is "the ratio of the number of transactions that contain the item set to the total number of transactions" [8], so support is the indicator for the frequency with which a certain combination occurs.

Confidence is the support for a given combination (e.g., **A** → **B**) divided by the number of occurrences of **A**. So high support indicates a frequent occurrence of a given combination (**A** + **B**), while high confidence indicates that, e.g., **A** often is found with **B**. So the confidence becomes a proxy for the likelihood of observing **B** given **A**.

Figure 1 illustrates the different levels of complexity of association rules defined and addressed in this research. Where the most simple association rule assumes that lack of input leads to **A** occurring, the next level assumes that if **A** occurs, **B** occurs with a given support and confidence and so forth. Note that links are unidirectional, and thus, **A** leads to **B** does not imply that **B** leads to **A**. In the context of mass customization, these complexities can be directly related to the configuration choices or bill-of-material of the configured products. As an example assume that customers choosing to use component **A** in their configuration also chooses with some confidence and support to include component **B**. Of these complexities of rules II–IV are investigated in this research to limit the scope.

This paper investigates two issues:

1. How the complexity of the association rules influences the number of rules that can/should be taken into account.
2. How the support and confidence influence the number of rules at a given complexity level of associations and compared to a higher level of complexity, i.e., investigate what is driving increases in number of rules, confidence levels, and/or support levels.

The resulting method investigates how complex a solution space is and how difficult it can be to, e.g., guide a customer through the customization process. The first point is investigated through identification of the number of additional rules created through adding a level of complexity at given level of confidence and support. The second point is investigated through ANOVA with confidence and support levels as independent variables and the number of rules and the factorial increase in the number of rules as dependent variables.

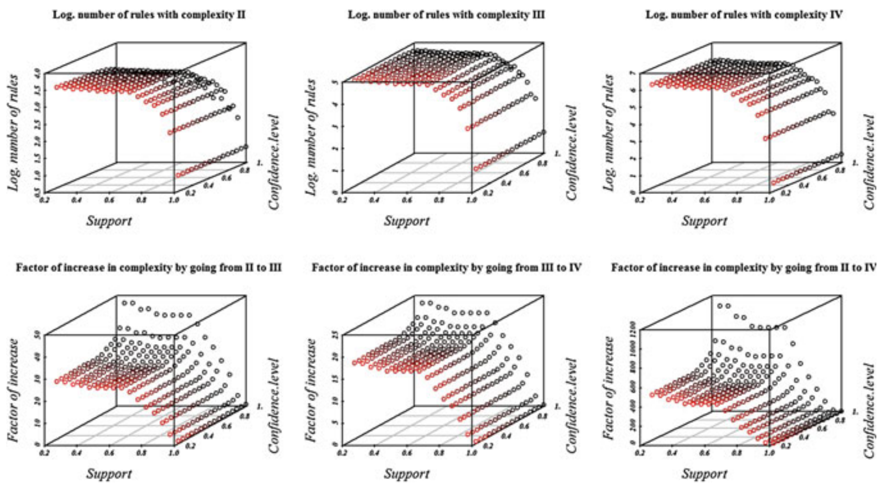

Fig. 2 *First row*: the logarithmic increase in the number of rules when going from one complexity level of rules to the next. *Second row*: factorial increase in complexity from one complexity level to another

The experimental setup is as follows: Confidence and support are varied from 0.25 to 1.00 in steps of 0.05, and all combinations of confidence and support levels for rule complexity II–IV are investigated. This gives $16 \times 16 \times 3$ (16 confidence levels $\times$ 16 support levels $\times$ 3 complexity levels) = 768 investigations that are carried out.

4 Results

The studied case contains 180 unique orders with 178 bill-of-material parameters that vary in inclusion/exclusion of a configured product. BOM items always included have been removed from the study, so that only BOM items that are actually configured are included. The method is implemented and tested in the open source software R using the package *arules* [9].

The results of these investigations on the case data are shown in Fig. 2. From Fig. 2, it is shown that the number of rules increases from in thousands, to the hundreds of thousands and to millions as one goes from a complexity of rules of II, to III and III to IV, respectively. A simple experiment of adding a further level of complexity to the rules indicates that tens of millions of additional rules are created by adding this complexity. This underlines that the even a limited number of orders can contain a very large number of association rules, when the complexity of these rules increases from simple rules (i.e., A → B) to more complicated rules.

By using ANOVA analysis, treat support and confidence levels as independent variables and the logarithmic number of rules (due to exponential behavior of the

Table 1 Overview of best ANOVA models excluding any non-significant variables

	Impact on complexity level II		Impact on complexity level III		Impact on complexity level IV	
	Estimate	Pr (>|t|)	Estimate	Pr (>|t|)	Estimate	Pr (>|t|)
Intercept	4.53	0.000	6.32	0.000	8.24	0.000
Support level	−1.99	0.000	−3.29	0.000	−4.75	0.000
Confidence level	−0.39	0.001	–	–	–	–
R^2		0.53		0.55		0.55
Adj. R^2		0.52		0.54		0.55
	From to II to III in rule complexity		From to III to IV in rule complexity		From to II to IV in rule complexity	
	Estimate	Pr (>|t|)	Estimate	Pr (>|t|)	Estimate	Pr (>|t|)
Intercept	38.30	0.0000	26.03	0.0000	703.68	0.0000
Support level	−36.35	0.0000	−23.20	0.0000	−824.22	0.0000
Confidence level	9.61	0.0000	2.85	0.0001	252.18	0.0000
R^2	0.76		0.80		0.78	
Adj. R^2	0.76		0.80		0.78	

number of rules) and the factorial increase in the number of rules as dependent variables. The best fitted models are given in Table 1.

It should be noted that in the case of the factorial increase from going from II to III and from II to IV in the complexity of the rules, the interaction between support and confidence levels is in fact significant. However, removing the interaction only lowers R^2 from 0.77 to 0.76, so the interaction has limited explanatory value and has been excluded. From the R^2 and adjusted R^2 values shown in Table 1, it is clear that a large part of variation in the factorial increase in the number of rules and the actual logarithmic values of the number of rules can be explained by a combination of the support and confidence levels.

For all three levels of complexity of association rules, the support level is the most significant variable in determining the number of rules created by using the association rules. In general, the analysis shows that the higher the support (i.e., the higher the frequency of occurrence), the lower the number of rules. This seems intuitively correct and can indicate a number of issues for the case. First, as the number of association rules is quite low when support is 0.90 or above (for II–IV, respectively, 117–545, 1,675–4,987, and 11,886–26,615, depending on the confidence level), the number of fixed BOM combinations with high use frequencies is low (taking 178 BOM items into account). Second, when support levels are low (0.25), the number of rules increases dramatically (for II–IV, respectively, 904–3,322, 42,315–92,583, and 989,015–1,676,487, depending on the confidence level). This implies that there are in fact a very large number of BOM combinations that are frequently used (even with confidence level 1.00) and implies a large degree of dependence inside the BOM structure in the particular case. For the complexity of association rules at II, the confidence level is also significant in explaining the number of rules. However, removing the confidence level only lowers R^2 from 0.53 to 0.52, so like the interaction discussed previously, it can be discounted from the discussion.

Of equal interest is how the number of association rules increases (for a fixed support and confidence level) when the complexity of the association rules increases. Interestingly enough, this depends both on the support level and on the confidence level, though again with the largest contribution from the support level. The R^2 values are *c*. 0.80 for the fitted response models, indicating a strong explanatory value of support and confidence levels. This is not necessarily intuitive. However, it implies that when increasing the complexity of the association rules to investigate the BOM dependencies, the support and confidence levels are non-trivial. Specifically, in the particular case, the response models imply that low support levels tend to have high increases in the number of rules when the complexity of the association rules is increased. In the sense of managing a solution space, the number of rules to consider is thus very much higher if the support levels are low. This could also indicate for the case that there are a large number of constraints in the solution space for combinations that are seldom used.

5 Implications

The knowledge obtained from the Apriori analysis can be utilized in a number of different ways. In this section, it is described for each mass customization capability, how utilization of the results can benefit mass customizers.

5.1 Solution Space Development

Solution space development concerns the identification and development of product variety. This implies also to revise a company's current product portfolio in order to consolidate it if necessary over time. This is typically done by removing unnecessary components or modules, which are seldom sold or which have a function that can be incorporated into other modules or components. This will generally imply lower manufacturing costs, similar to general design for manufacturing principles [10]. In this context, the results of the Apriori analysis could be utilized to identify candidates for combining two modules into one module. Often, mass-customized products are modular, and the modules are used to accommodate product variety by allowing different variants of a certain module type. However, this variety comes at a cost and reducing the number of module variants will usually imply lower manufacturing costs. The results of the Apriori analysis will indicate which modules are often sold together. If certain modules are always sold together, it would be natural to consider joining these two modules. There are, however, other considerations which could limit the possibilities of joining two modules, e.g., if the two modules are supplied by different suppliers, utilize different manufacturing technologies, have different life cycles, etc., which needs to be taken into account. If the module, however, could be combined, this could imply a faster assembly process, as fewer modules would need to be assembled, lower fabrication cost of modules, a simpler product structure with lower administration costs as well as a simpler product family model and a simpler configuration system.

5.2 Robust Process Design

Another natural approach to using the information gained from the Apriori method would be to use this to design both planning processes and inventory management. In production planning [11], the typical approach is to batch similar products/components for planning purposes [12]. However, in mass customization, this is typically one of the main planning challenges, as there are by definition no standard products to group for production, so products are either made-to-order or assembled-to-order from a central inventory of components/modules. Standard inventory management would then imply that components/modules are grouped based on their individual characteristics (price, demand profile, lead time, supplier, etc.) [13]. However, this implies that items can be managed individually. The study presented in this paper clearly concludes that a large number of components directly or indirectly are always sold together. This strongly implies that both the inventory management approach and the subsequent planning approach need to take these dependencies into account.

5.3 Choice Navigation

The capability choice navigation is defined by Salvador et al. [3] as "Support customers in identifying their own solutions while minimizing complexity and the burden of choice." Hence, this capability is related primarily to the capabilities of the configuration system and its ability to configure a variety of products. The ideal product configuration should, after a customer has finished a configuration, leave the customer with the experience that the process has not been unnecessarily difficult to perform and the customer has been able to match his or her needs exactly to a specific configuration of a product [3].

The knowledge obtained from the Apriori analysis can be applied almost directly to improve the product configuration process. If it is determined that customers nearly always select component B given component A, it would be obvious to introduce a "soft constraint" in the product configuration, which would imply that once a customer selects component A, then component B is automatically chosen as default. Contrary to a hard constraint, a soft constraint would allow the customer to choose a different component than B following this.

However, selecting B automatically would imply less effort from the customer for performing the whole configuration process, yet leaving the flexibility to alter the automated selection.

The introduction of soft constraints should, however, only be made if there is a high confidence for a certain rule, i.e., component B is almost always chosen given component A. If the confidence is lower, a different approach could be taken. The Apriori analysis may in some cases indicate that if a component A is selected, then components B, C, or D are chosen equally frequent; however, other components may also be chosen. In this case, in an actual configuration, the customer is usually presented with a number of different components to choose from (e.g., B, C, D, E, F, and G). However, if this list is sorted according to confidence, then the most likely component would be on top of the list and the least likely in the bottom. This would, like the introduction of soft constraints, improve the configuration process by reducing the necessary effort to perform the configuration process.

6 Conclusions

Establishing the links between components in configured products can potentially significantly improve the ability to control the solution space and choice navigation for customers. Previous research has applied the Apriori data mining technique to establish these links. This paper focuses on a specific case and analyzes 180 sold configurations and their link to support and confidence levels used in the data mining.

From the case study, it can be seen that number of rules to consider increases dramatically as a function of the complexity of the rules. Furthermore, it can be concluded that in particular, the support levels are critical when investigating the rules. In general, low support levels lead to many rules and to disproportional large increases in the number of rules as the complexity of rules applied is increased.

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A Method for Specification of Multi-variant Products Using Degrees of Freedom of Shape Attributes in Product Structures

Paul Christoph Gembarski and Roland Lachmayer

Abstract Planning multi-variant products in the early stage of the design process is still a challenge. In the present paper, a specification technique is introduced in order to define multi-variant products using degrees of freedom of shape attributes (in the following shape-DoFs) within product structures. Our goal is to plan variety at the beginning of product development actively. Shape-DoFs are classified in the fields of shape attributes (dimension, position, shape, as well as their combinations) on the one hand and mandatory or optional components on the other hand. Setup on this taxonomy graphical symbols are introduced for the use in product modeling. As application example, a pipe rack is modeled.

Keywords Specification technique · Product configuration · Complexity management · Product structure · Shape degrees of freedom · Product customization

1 Introduction

Market development in many industrial sectors shows tendencies to more customer specific and technically more complicated products. The customer's desired and perceived diversity and the desired individuality of products should be dealt with a minimum of organizational efforts.

In the present paper, a specification technique is introduced in order to define multi-variant products using degrees of freedom of shape attributes (in the

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following shape-DoFs) within product structures. Usually, the product structure and the component's shape are considered individually. For a certain products, implementing both has advantages for product modeling [1].

1.1 Motivation

Planning multi-variant products in the early stage of the design process is still a challenge. In particular, using modular product designs is favorable regarding design efforts for customizable products, which means assembling as many compound products out of only a few standardized components or subassemblies [2]. The consequence is that relations between these components have to be reduced to the minimum. Ideally, a sub-function is realized solely in one module which comes with standardized interfaces. Therefore, the exchange of separate modules due to either functional or design aspects is possible. Diversity so is realized using optional components.

The approach presented in the present paper has different aims. According to our method, a component's degrees of freedom are intentionally used in order to plan and benchmark diversity regarding technical and economical aspects. On the other hand, those degrees of freedom can be understood as design variables which are used in later CAD models.

1.2 Structure of the Paper

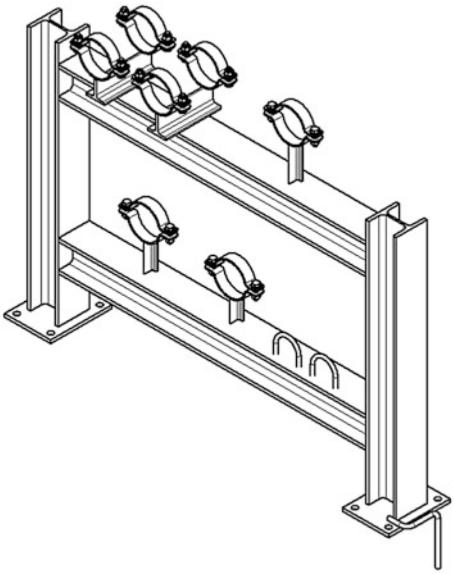
In the following Sect. 2, previous approaches of modeling product structures of multi-variant products are presented. Sect. 3 then shows our method using shape-DoFs. An application example (a welded pipe rack) then visualizes the concept. Closing the paper, Sect. 4 contains a brief summary and drafts prospect questions we are dealing with.

2 Structuring Multi-variant Products

Product structuring can be done in different ways. Generally accepted is the representation using either assembly structures (the structure of physical components), structures of functionality, or product architectures [3].

The assembly structure resembles the manufacturing and assembly sequence, whereas the structure of functionality describes the relation of main- and sub-functions. Both views on the product structure are mapped within the product architecture which translates functions into physical components. Regarding the assembly structure, it is represented by either a hierarchical component tree or graphs. Diversity therein is represented as alternative or optional components.

Fig. 1 Pipe rack



In order to describe variance in product structures, variant trees where suggested [4]. There a component's different occurrences are placed side-by-side in a hierarchical tree, so the last row corresponds to the maximum count of all product variants. Using restrictions expressed by configuration rules or interdictions of application, the optimal amount of product variants can be worked out. Therefore, all occurrences of the product and its components have to be specified before.

A different approach is the use of degrees of freedom in product structures which is discussed recently. In one representation, so-called cardinalities were implemented which have to be understood as variables for distinct component occurrences [5, 6].

Advancing is another method which distinguishes different areas in the product structure. Therefore, fixed and scalable arrays, optional and mandatory alternatives, and predefined and general spaces have to be differentiated in order to adapt a product to new market conditions or functional requirements [7].

3 Shape-DoFs Within Product Structures

Picking up this approach, we define the general degrees of freedom using shape and body attributes [8]. First of all, in this chapter, a taxonomy of shape-DoFs is introduced. Afterward, these DoFs are transformed into graphical elements which describe a product's components.

At the end of the chapter, an application example (a welded pipe rack, Fig. 1) is modeled with shape-DoFs.

Table 1 Taxonomy of degrees of freedoms in product structures

	Mandatory	Optional
No DoF		
Selection/choice		
Position		
Size		
Shape		
Layout	n.a.	

3.1 Taxonomy

Regarding the superior classification of product components, mandatory and optional elements have to be distinguished.

Choosing one component out of multiple alternatives is already a degree of freedom. Furthermore, shape attributes of faces and bodies have to be differentiated as DoFs of position, size, shape, and count result. These can be used solely or in combination.

Also to be considered as DoF are predefined spaces within the product structure when a component is designated but yet not detailed. In principle, such an element can be modeled through a combination of all shape-DoFs. Not to mix it up with components where the DoFs are used as distinct design variables, another DoF layout is defined. An overview of shape-DoFs is given in Table 1.

3.2 Symbols

The symbols are built up in three elements (Fig. 2). The upper part is the so-called usage marker. It indicates whether the component is mandatory (rectangular) or optional (triangular). The mid part contains the information field with the component's name or identifier. It is completed with the quantity n on the lower left and a value range $[a \ldots b]$ on the lower right (e.g., when a position shall be between 100 and 200 mm, see below). The bottom part is the shape-DoF marker.

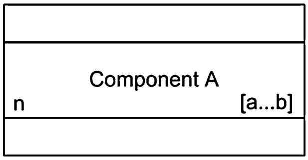


Fig. 2 Symbol

3.3 Base Symbols

Base symbols are used for fully determined and fixed components which don't have any DoFs. In order to improve readability, we recommend labeling the top node with another color (see example above *Mounting Foot*, Fig. 3). The usage marker identifies the components *Base Plate* and *Beam IPB 100* × *800* as mandatory, the *Flange Plate* is optional.

3.4 Selection of Alternative Components

Selections within the product structure are represented by a symmetric triangle in the shape-DoF marker and a gray information field. These nodes have to be understood as placeholders in the product structure. They get replaced by the distinct-selected component and do not resemble any BOM elements. In the example above, the pipe support no. x can be set up either as double brace or as U clamp (Fig. 4).

3.5 Components with Shape-DoFs

As shape-DoFs position, size, and shape are differentiated as well as their combinations (a component's count also resembles a shape attribute; this is indeed represented by optional components in the actual model).

If variable positioning of a component is intended, the DoF marker is a cut-out rectangle (Fig. 5). The value range in this example expresses that the double brace has to be mounted in between 160 and 360 mm measured form the base line. The representation can be extended to all Cartesian coordinates (variable position in *X*, *Y*, and *Z*).

Variable size is shown by a trapezoid in the DoF marker (Fig. 6). In the example above, the length of the IPB100 beam may vary between 80 and 800 mm. The size DoF might additionally be characterized by a certain step, e.g., the beam's length may only be varied in a 10-mm step.

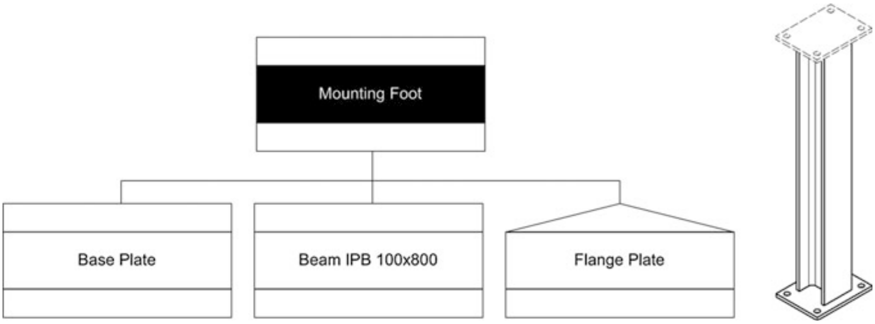


Fig. 3 Base symbols

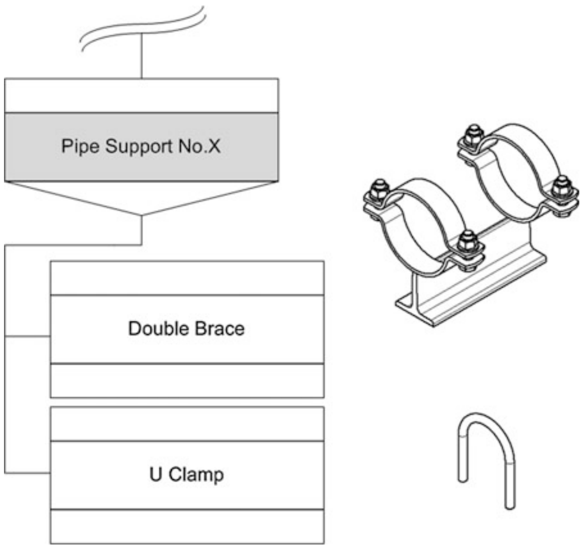


Fig. 4 Selection symbols

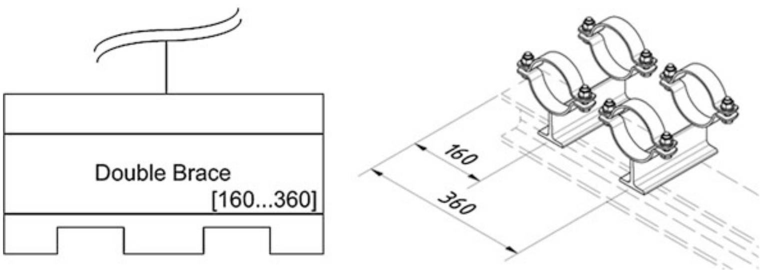


Fig. 5 Symbol for position DoF

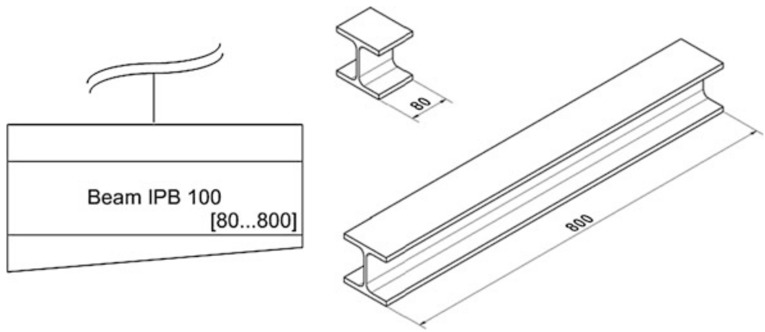


Fig. 6 Symbol for size DoF

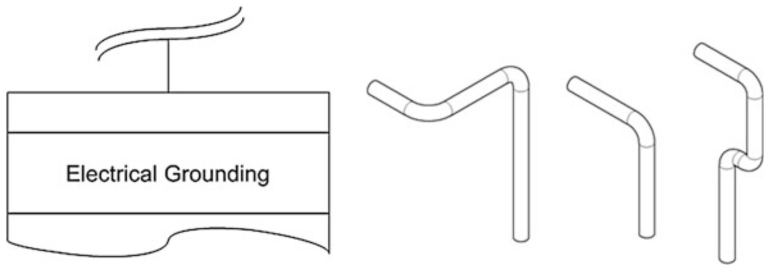


Fig. 7 Symbol for shape-DoF

The shape-DoF is characterized by a freehand line in the DoF marker (Fig. 7). Regarding modularity, the interfaces to neighbor components should be standardized and must not be affected by the shape. In other words, an installation space has to be defined within the shape that can vary.

In addition, all possible combinations of shape-DoFs have to be allowed (Fig. 8).

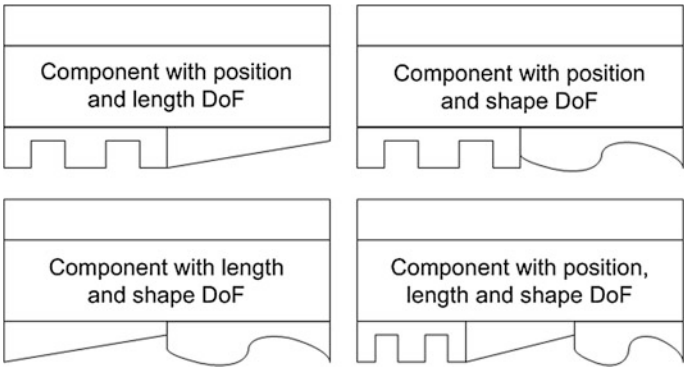
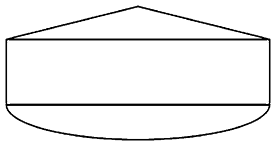


Fig. 8 Symbols for combined DoFs

Fig. 9 Layout DoF



3.6 Defined Spaces for Non-detailed Components

Reasonably non-detailed components only may be optional components. In this case, a sub-function is planned, but yet not designed (this will, e.g., be done when this sub-function is explicitly demanded by a customer). The DoF marker is a bend (Fig. 9).

3.7 Cut-to-Fit Modularity

Our concept is able to represent PINE's cut-to-fit modularity using the size DoF which also can be done on assemblies like in our application example below [9]:

This single-brace pipe support was identified as company-specific standard part within a design project. It is manufactured in-house from a clamp and a *t* profile. The single brace is prefabricated in larger amounts in three distinct lengths.

When used in an assembly a suitable brace is taken and then cut-to-fit. So, the size DoF is in the subassembly *single brace* but not in its parts (Fig. 10).

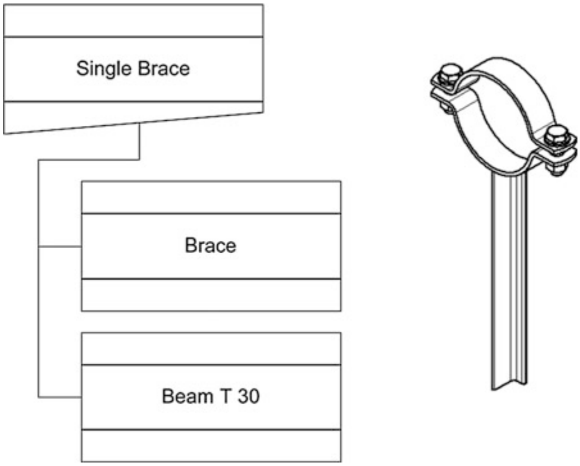


Fig. 10 PINE's cut-to-fit modularity modeled through shape-DoFs

3.8 Summary Application Example Pipe Rack

Using the simplification that only one diameter of pipe supports is used, the above product model represents the application example (Fig. 11).

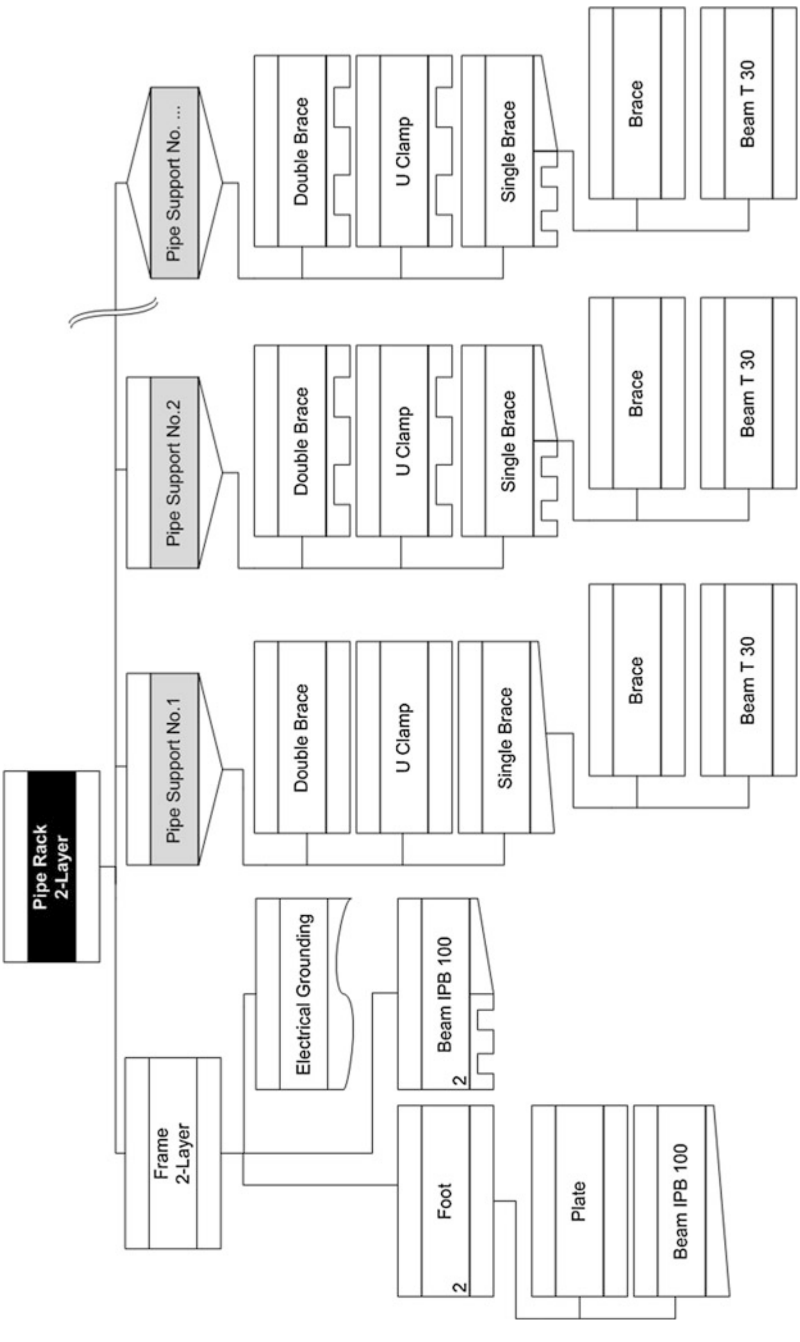


Fig. 11 Pipe rack modeled through product structure with shape-DoFs

4 Conclusion

In the present paper, a method was introduced in order to model a product's variability using shape-DoFs within the product structure. The goal is to actively plan variability in the early stages of product development.

Until now, we used three shape attributes (position, size, shape) for modeling. It will be examined whether other attributes lead to other necessary shape-DoFs. In the application example, a welded assembly was examined. In addition, it has to be proved that other types of products can be modeled as well.

In our example, all shape-DoFs are furthermore decoupled which means that there is no functional or geometric relation between them. This simplification has to be withdrawn, and a possibility for linking shape-DoFs has to be implemented.

Regarding economic aspects, we hypothesize that different shape-DoFs lead to different costs in manufacturing. If a size DoF can be realized through another cut length, the position DoF within a welded assembly might require new or adapted jigs or fixtures. Special attention has to be paid on the effects of the shape-DoF. Recent manufacturing techniques like rapid prototyping and additive manufacturing offer new potentials there. Summarized, it has to be examined whether cost scenarios can be derived of shape-DoFs.

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A Profile Chart Approach for Defining the Solution Space of a Production Network

Lars Skjelstad and Maria Kollberg Thomassen

Abstract Norwegian leisure boat manufacturers have experienced a transition from large to small production series during the last years following a general decline in demand. They are forced to transform large-scale operations into handling small volumes of highly customized products while maintaining the same level of cost efficiency. The literature presents several frameworks that can help to "crack the code" of mass customization. However, the mass customization strategy is still little understood and deployed in industry. There is thus a need to develop more in-depth understanding of how companies can get started and enhance their mass customization capabilities. This paper presents a chart approach for defining the solution space of a leisure boat production network. Opportunities and limitations of the suggested approach are also addressed.

Keywords Mass customization · MC capabilities · Leisure boat industry · Production network · Profile charts · Solution space definition

1 Introduction

Mass customization is the capability to offer individually tailored products or services on a large scale [1]. Furthermore, it is about developing, producing, marketing, and delivering affordable goods and services with enough variety and customization possibilities that nearly everyone finds exactly what they want [2]. The concept offers new opportunities to companies combining a mass production

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tradition with a high level of customization, maintaining high efficiency while offering highly customized products. MC has got great attention during the last two decades, but its adoption in practice has been slow seen in terms of the increasing interest and major potential [3–5]. Even though the concept is easy to describe, it is not that easy to deploy.

The literature presents several frameworks, e.g., [6, 7] companies can use to investigate and "crack the code" of MC. However, existing frameworks are rarely based on empirical studies, and industry therefore often finds it hard to make practical use of the knowledge in the literature. There are several EU research projects addressing implementation issues in various industries, for instance, the automobile industry and the clothing and footwear sectors. The "Customization 500" survey [8], studying 500 companies that have started with mass customization, showed that 20 % of the companies have stopped or are closed down after one year, while the ones that succeeded show high revenues. Companies need to be better apt to realize the MC strategy and see the opportunities in their respective industry. Research also shows that there are several unresolved issues regarding the practical implementation of MC and that most conclusions are drawn from limited case examples or based on educated guesses from individual authors rather than from empirical evidence obtained through exhaustive research [9].

Charts are sporadically used to illustrate MC capabilities in research [4]. However, a profile chart approach has not been systematically investigated in depth as an analytical tool for a supply chain.

For manufacturing companies starting with MC, perhaps the most important decision is how to define the solution space, what to offer. An investigation to map customer expectations is needed. From a manufacturer perspective, too many choices might be just as big a mistake as too few. Also, capabilities in own organization as well as for key actors in the supply chain must be mapped to see how well customer preferences can be met. Further, market expectations normally alter over time.

Hence, we suggest using what we denote "profile charts" to compare initial gaps between market needs and the supply chain's ability to meet them. It is a quick and visual approach to get a start-off point, covering central actors in the supply chain. An example chart of the number of variants preferred by customers regarding a selection of leisure boat attributes is shown in Fig. 1.

The profile chart shows the ideal solution space seen from a customer point of view. We suggest that this initial picture should be compared to what the supply chain is able to offer.

The purpose of this research is to present a quick and easy approach to define the solution space of a production network by evaluating the trade-off between cost, lead time, and customer satisfaction. Capabilities in the whole supply chain should be taken into consideration.

The paper is structured as follows. The applied research approach is described followed by a presentation of the theoretical frame of reference. Findings from applying the chart approach to define the solution space of a leisure boat production network are presented and discussed.

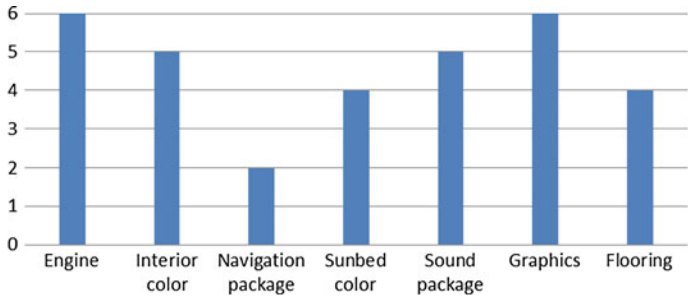

Fig. 1 Example chart of customer preferences regarding the number of variants per attribute for leisure boats

2 Research Approach

In order to design a profile chart approach for defining the solution space of a production network, a set of MC capabilities were identified in the literature. These were used to develop charts that could graphically illustrate MC capabilities. The charts were tested in a case-specific empirical setting including a network of three companies in the leisure boat industry.

Compared to simpler products such as sun glasses and shoes, boats are more similar to cars and more complex products. The manufacturing time of a boat is more than 10 weeks and can out of season be even longer. This opens for good planning of deliveries from the supply chain into the major assembly project.

MC capability charts were designed based on data collected from the companies. A mix of qualitative and quantitative data was used. Data were collected through interviews and from internal documentation. Company representatives were involved in the development of profile series during workshops.

Focus in this study is on the Norwegian leisure boat industry. It has experienced a major decline during the last few years due to the financial crisis and increased international competition. Manufacturers faced a major challenge of operational efficiency as production volumes diminished, resulting in batch sizes of one. At the same time, customers preferred a higher degree of customization in their boats. A potential arose for leisure boat manufacturers to adopt a MC strategy to more efficiently align their organizations with market and customer needs.

The boat manufacturers could traditionally be characterized by a high level of handcraft with sporadic customization rather than the mass production tradition, which is typically among some companies that seek to develop their MC capabilities. They have not yet exploited the possibilities that might be for them in the mass customization strategy; they are not both customer centric and effective at the same time. The decrease in volumes after 2008 was challenging and caused a necessary shift in strategy from large volumes to small volumes and from a generic market to more dedicated customers. From a theoretical point of view, *smart customization* is a more proper term for the business today rather than *mass* *customization*. A downsizing of the business was not enough; they also needed to develop their industrial effectiveness and handling of individual customers preferences in a more competitive way. They went from small series to one of a kind and from handcraft to smart customization. Employing the thinking of mass customization could prepare the companies for a future increase in the series volumes. The need for a defined solution space checked for cost and response time considerations was essential. A case study strategy was applied. The investigated case is a production network of three companies;

- a boat manufacturer that manufactures high-end leisure boats
- a windscreen supplier that provides windscreens to the boat manufacturer
- supplier of components made of stainless steel that provides a range of various components to the boat manufacturer.

Even though the charts were developed for a specific leisure boat context, the intention was to provide a general approach that can be applicable also for other industrial contexts.

The charts presented in this paper are primarily designed to illustrate examples of relevant boat attributes. They are based on the original charts designed in the research project but have been simplified and made more explicit to show the overall principles of the profile chart approach.

3 Theoretical Frame of Reference

The competitive advantage of MC is based on combining the efficiency of mass production with the differentiation possibilities of customization [10]. MC is further about developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want [2].

MC is a customer-centric business strategy applicable to most companies, provided that it is appropriately understood and deployed. In order to benefit from MC, companies need to think of it as a process for aligning an organization with its customers' needs [6].

There are several examples of frameworks available in the literature that can be used to characterize a company's ability to carry out MC operations. Salvador et al. [6] propose three common capabilities that will determine the ability of a company to mass customize its offerings:

- Solution space development: Identify the product attributes along which customer needs mostly diverge. The solution space defines what a company will and will not offer to its customers.
- Robust process design: Reuse or recombine existing organizational and supply chain resources to fulfill a stream of differentiated customer needs
- Choice navigation: Support the customers in identifying their own solutions, while minimizing complexity and the burden of choice.

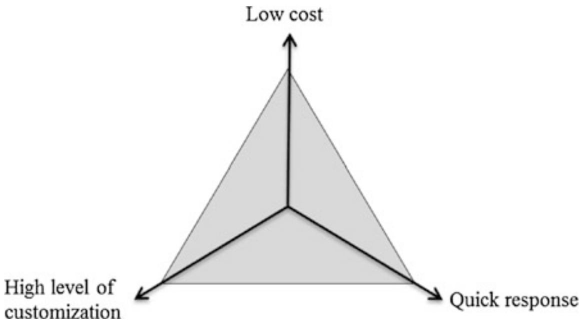

Fig. 2 Order-winning criteria for MC manufacturers [7]

According to Skjelstad [5] and Alfnes and Skjelstad [7], order-winning performance objectives for MC include cost, customization, and responsiveness, and companies with strong MC capabilities should be able to deliver customized products quickly and at low cost (Fig. 2). This means that companies that seek to improve their MC capabilities should focus on performance improvements related to customization, cost, and responsiveness and find an appropriate balance between the three dimensions.

Although the literature underlines the importance of strong MC capabilities not only of single companies but also of entire supply chains or networks [1, 9–11], there is limited research dealing with MC capabilities in a supply chain perspective. The frameworks presented above primarily provide structures for characterizing and developing MC capabilities of single firms and do not specifically address MC capabilities of several companies in production networks. However, the dimensions of these frameworks are also relevant for developing MC capabilities of networks as a whole.

The solution space concept is used to define boundaries for customers' "legal" choices. The solutions within the defined space should represent the attributes most sensitive to customer preferences. Since MC capabilities not only relate to customization but also involve cost and responsiveness, the proposed solution space must be evaluated also along these two dimensions.

4 Findings

The suggested approach reflects three perspectives including the customer, individual company, and network of companies and follows a set of steps, see Fig. 3. First, a chart was developed to represent customers' preferences regarding attributes and number of variants. This was compared to a chart showing the current situation with regard to the network's current offering, in order to identify the gap, or development potential. The development potential was then considered in terms

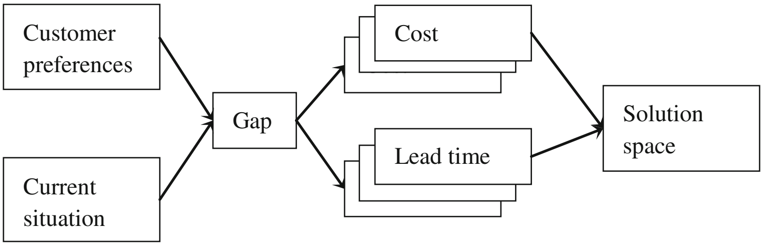

Fig. 3 Overview of steps in the suggested chart approach

of both costs and lead times of the production network, before the solution space of the network was defined.

4.1 Revealing the Gap by Comparing Customer Preferences with Current Situation

The customer preference chart (Fig. 1) was combined with the current situation regarding the number of variants per boat attribute offered by the boat manufacturer in Fig. 4.

This chart revealed a gap or mismatch between the customers' preferences of number of variants and the number of variants that were currently offered by the boat manufacturer on all attributes except from "navigation package." With regard to "engine," "sound package," "graphics," and "flooring," the number of variants preferred by customers was higher than what was offered, while for the attributes "interior color" and "sunbed color," the boat manufacturer offered more variants than was asked for. Except for the "navigation package," there was a gap between customer preferences and variants offered. This means that there was a development potential of increasing the number of variants for some attributes while reducing the number for others.

4.2 Cost

In a robust process perspective, it was important to consider not only the manufacturing processes of the boat manufacturer, but also those of the suppliers. The development potential in terms of increased or decreased number of alternatives was therefore considered related to relative cost or savings of the boat manufacturer and the two suppliers. An aggregated overview of the costs and savings of the network as a whole is shown in Fig. 5.

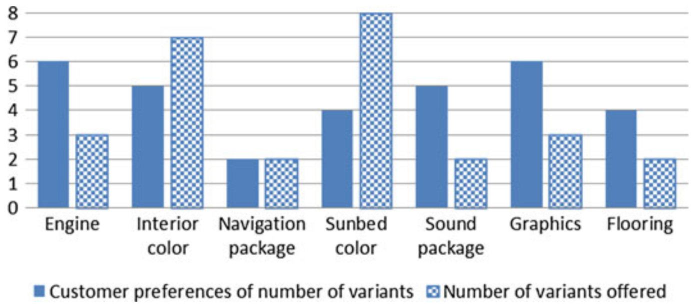

Fig. 4 Customer preferences and current situation of variants offered

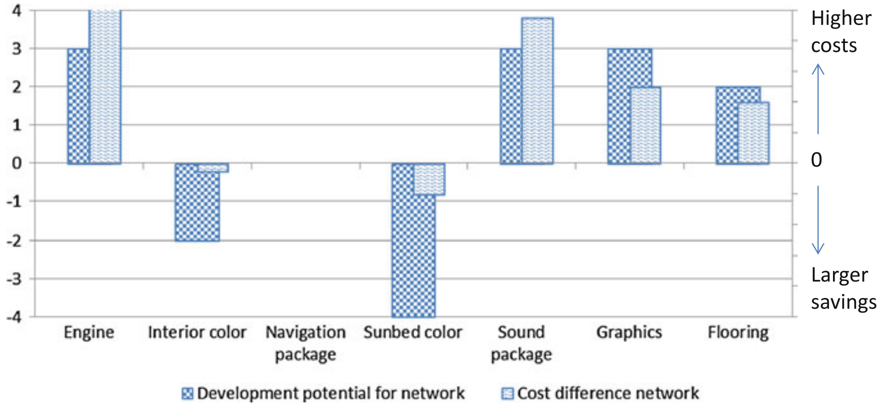

Fig. 5 Aggregated cost difference for the identified development potential of the network

The chart indicates for example that an increased number of engine variants imply a relatively high cost for the network. This is due to brackets, spare parts, testing, negotiations with engine manufacturer, etc. Furthermore, reducing the number of interior color variants will have minor implications for reduced costs in the network. This means that in terms of cost, the most profitable measures for the network would be to increase the number of flooring variants and to reduce the number of sunbed color variants. The other alternatives were less evident, as a reduced number of interior colors only represent minor savings and increased number of sound packages and graphics imply relatively higher costs. The chart gave a quick overview of the costs and benefits associated with increasing or reducing the number of variants offered by the network.

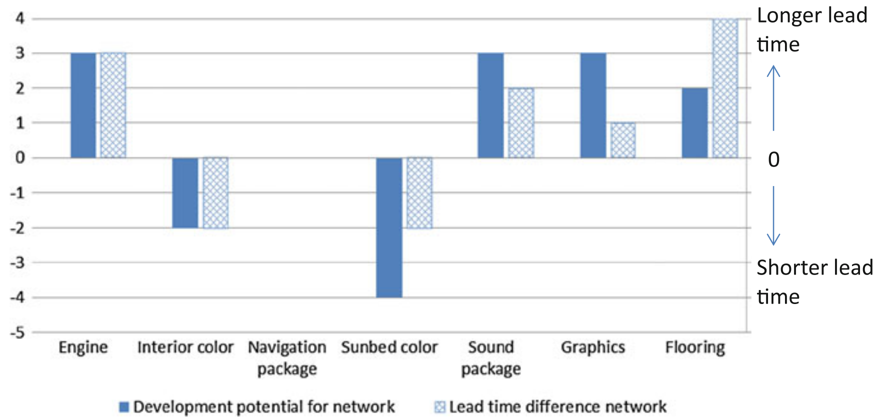

Fig. 6 Aggregated lead time difference for development potential

4.3 Responsiveness

A similar chart with regard to lead times was developed. The profile chart in Fig. 6 was used to reveal the relative lead time difference of the production network with respect to the development potential of attribute variants. An increased number of engine variants for example would imply longer lead times of the network on an aggregated level, while an increased number of graphic variants had little impact.

The profiles were again constructed by checking capabilities and consequences for the participating network actors, following a "weakest link" type of logic.

4.4 Solution Space

Based on the cost and responsiveness perspectives of the entire production network, a chart showing the solution space in relation to customer preferences was developed, see Fig. 7.

The chart shows that an increase or reduction in the number of variants for certain attributes implies several benefits for the network in terms of both costs and lead times. A chart was also developed to show a comparison of the current situation and the suggested solution space, Fig. 8.

The development of the solution space is a continuous process, where the gap compared to customer preferences must be sought closed. In our case, the manufacturer has as an example to work on how to offer more engine options efficiently.

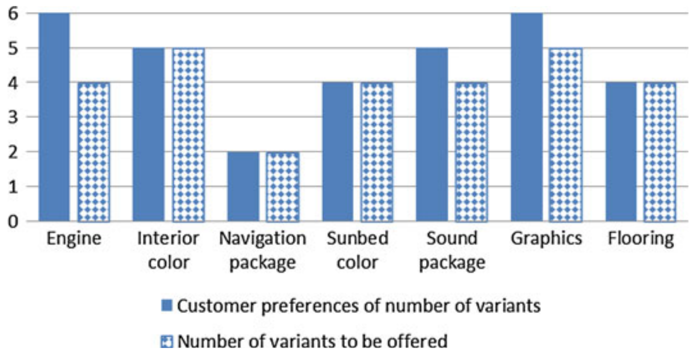

Fig. 7 Solution space: Number of variants to be offered compared to customer preferences

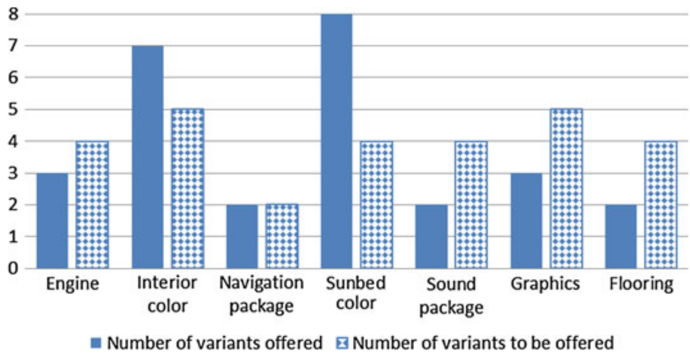

Fig. 8 Comparison of current situation and the defined solution space

4.5 Opportunities and Limitations

Several opportunities and limitations of using the chart approach for defining the solution space of the production network were revealed (Table 1). These findings are based on the experiences from testing and developing charts in the case companies of the production network.

The profile charts constituted an efficient tool for defining the solution space of the production network by illustrating and visualizing customer preferences and the current situation, and as a means to identify gaps between customer preferences and company network charts. They further provided a foundation of collected facts of current status for strategic discussions about direction of major improvement potential.

Moreover, the charts constituted an efficient tool for discussing MC strategies with suppliers on how the network can improve the MC performance and better match customers' preferences. The approach implied increased insights among the

Table 1 Opportunities and challenges with the suggested approach

Opportunities	Challenges
Illustrated and visualized customer preferences and the current situation	Required access to reliable data
Identified gaps between customer preferences and network offerings, a good foundation for strategic discussions in the network	Did not give a precise measure of MC performance
Increased understanding of challenges and opportunities related to developing MC capabilities	Limited customer orientation insights of suppliers
A quick method based on "trends" more than extensive data gathering	

company representatives of challenges and opportunities related to building MC capabilities in the network.

A major challenge was to get access to reliable data for characterizing capabilities. In the case companies, operations were mainly managed manually and ad hoc and ERP or similar systems were only used to a limited extent. This implied that we had limited access to consistent data for developing the charts, especially those related to costs and lead times.

Another important consideration was that the charts did not give a precise measure of MC performance. Rather, they intended to give improved understanding of major MC capabilities and how these could be operationalized and conceptualized.

Applying the charts in a network perspective revealed a major challenge related to customer orientation. The leisure boat manufacturer "owned" the relationship with the customer, while the suppliers had no direct interface toward the end user of the final product. This implied that the suppliers had little insight into customer preferences as they are defined in the MC framework. In order to ensure a highly customer-centric production network including the suppliers, the boat manufacturer would have to share information about customer preferences with its suppliers, for example via a Web-based supplier portal. The charts led to an increased awareness of customer preferences among the suppliers in the network.

5 Conclusion

The *profile chart* approach was used in this study to define the solution space of a production network in the leisure boat industry. Findings show that this approach constitutes an efficient instrument for describing current situation and customer preferences as well as directions for future improvement potential with regard to the manufacturing network MC capabilities. The characterization itself can help companies to better understand the MC mechanisms.

In a production network perspective, the approach can be used to improve the understanding of customer preferences to producers and suppliers and a better understanding of current status and challenges of other companies in the network. The importance of the network perspective has been little addressed in previous research.

It is important that the key suppliers in the chain are involved to ensure a true picture of the network MC performance, since producers depend upon their suppliers. We experienced that reduced lead time for one attribute did not affect the total lead time, but could be offered as a postponed decision point for customers.

This research has demonstrated how the solution space of a leisure boat production network can be characterized by using charts. The aim of this approach has been to efficiently visualize and concretize the MC concept to companies so that the strategic mechanism can be appropriately understood and deployed. The chart approach was developed based on a combination of literature studies and empirical data collected from a production network in the leisure boat industry.

This research may have implications both for researchers and practitioners. The chart approach provides a starting point for researchers addressing MC capabilities and MC performance measurement. It also provides a practical tool for managers who seek to improve their MC capabilities and performance, as well as to clarify the meaning of the MC concept in organizations. It makes it easier to bark on the job of creating an understanding of consequences for the whole network when altering the solution space.

This study has several limitations that give opportunities for further research. Since results of this study are based on a single context in the leisure boat industry, it is suggested that the chart approach should be tested in other industrial contexts to enhance the validity. Due to limited access to reliable data, the study mainly presented example charts that can serve as a starting point for designing more refined chart templates in future studies.

Future research is needed to further develop the approach, designing a more comprehensive analytical management instrument for analyzing and improving MC qualities. A few measures for MC capabilities for the leisure boat production network were identified in this study that can be further developed in terms of sharpness and preciseness for assessing MC capabilities.

Moreover, the charts constituted an efficient tool for discussing MC strategies with suppliers on how the network can improve the MC performance and better match customers' preferences. The approach implied increased insights among the company representatives of challenges and opportunities related to building MC capabilities in the network.

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Applying the 5 WHYs to Identify Root Causes to Non-completions in On-Site Construction

Søren Lindhard

Abstract In on-site production, mass-customized subproducts are assembled through standardized processes. The production is pushing mass customization to the edge by producing unique and complex products. Due to the project structure, it has proven difficult to avoid repetitions of problems and to learn from mistakes. A central part of the control framework Last Planner System is to identify not completed activities to identify root causes and to learn. One tool to investigate root causes is the 5 WHYs approach. The 5 WHYs approach has been applied in a case study research to analysis the root cause to not completed activities. In total, 17 non-completed activities were registered and analyzed. To reduce non-completions, the risks each activity is carrying should be analyzed and understood, the product should be followed to identify problems early and to reveal time for intervention, and finally, communication on-site should be strengthened.

Keywords The 5 WHYs · Lean construction · Root cause analysis · Last Planner System

1 Introduction

Production in on-site construction projects is said to be based on engineering to order where an individual customization of the unique product takes place. Despite the uniqueness of the end product, construction projects contain a lot of standardized work process and mass-customized prefabricated subproducts. Mass customization is understood in relation to Tseng and Jiao's [1] definition "producing goods and services to meet individual customer's needs with near mass production efficiency."

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Even though construction projects can be viewed as simple assembling of mass-customized subproducts, the project structure, consisting of a temporary organization containing competing contractors, makes it difficult to standardize, to schedule, and to learn, especially between projects.

When mass customization is pushed to the edge, the products are becoming close to unique and the production is reminding of one-of-a-kind production as known in the construction industry. This high level of mass customization is making it very difficult to keep control of the production. To improve, mass-customized production should look toward the construction industry, which is experienced in handling "extreme" customization. Instead of planning based on the product structure, like it is normal for standard production, planning is shifted to an activity-based approach. In other words, the activity structure is often more invariant.

To handle "extreme" customization, the on-site production control principle Last Planner System (LPS) focuses on securing schedule reliability. Despite the construction industries, experience in handling "extreme" customization learning is still essential. Therefore, a part of the LPS is to learn from mistakes to avoid any future repetitions [2, 3, 4]. According to LPS, "the starting point for improvement in planning is measuring the percentage of planned activities completed PPC, identifying reasons for non-completion, and tracing reasons back to root causes that can be eliminated to prevent repetitions" [2]. Non-completions, which are defined as activities not completed according to schedule, are a part of on-site construction projects [5]. Non-completions decrease on-site productivity by creating interruptions in the work flow.

Root cause analysis is the discipline of identifying the cause to non-completions [6]. Instead of fixing the symptoms to recurrent and pernicious problems, the idea of root cause analysis is to identify the root causes and to prevent the problem from re-occurring [6, 7]. Root cause analysis plays a central role in the lean philosophy and is necessary to ensure continuous improvement by pursuing perfection [6]. As part of the lean philosophy, the 5 WHYs technique was introduced to capture and analyze data [8].

The 5 WHYs is a simple technique where five WHYs is asked to systematically uncover each layer to the occurred problem and to thereby reach its root [9, 7, 8]. The root cause is then eliminated to prevent the problem from reoccurring [7, 8]. Despite the importance of root cause analysis, the 5 WHYs is only rarely applied in practice in in-site production [10]. The reasons to why the 5 WHYs is only rarely applied is, besides a tendency in on-site production to de-emphasize root cause analysis, the difficulty in identifying the problems emerging on-site [10]. Tsao et al. [10] found that the trades working on-site not necessarily do complain about experienced site problems and identified 3 key reasons:

1. That the problems contractually often are the trade's responsibility.
2. A determination of which battles to fight. More "important" problems are addressed.

3. Pride and the fear that complaining will result in a poor reflection of the trades skill. Instead they believe that workarounds are how the problems are supposed to be solved.

This research study is based on the research hypothesis that the 5 WHYs technique will increase learning in on-site production, and it is made as an example to how the 5 WHYs can be applied in on-site construction. By registering site problems and identifying specific root causes, the lessons learned is estimated. The 5 WHYs technique is known from the Toyota Production system and can be directly used in mass-customized production as an instrument for learning.

2 Methods

The research is conducted as a qualitative research and consists of a one case study. A qualitative approach was selected to understand the context with surrounds a construction project and to enable identification of root causes to non-completions. Moreover, the context is important because it forms and influences the results [11].

The case study research was carried out by the following three steps: 1) Getting started, 2) selecting case, and 3) choosing crafting instruments and methods, which are presented in Eisenhardt's [12] guidelines for case study research. Getting started includes the definition of the research focus and the related research question. The selected construction case was followed with focus on identifying root causes to non-completed activities in the Weekly Work Plan. The root cause has been identified by applying the 5 WHYs technique. It is important to keep a clear research focus, to ensure that the correct data are collected, and to avoid being overwhelmed by a massive volume of irrelevant data [12]. Mintzberg [13] states it like this "No matter how small our sample or what our interest, we have always tried to go into organizations with a well-defined focus—to collect specific kinds of data systematically."

On single-construction case was followed. The case was selected through industry contacts, and it was ensured that LPS was applied and that a PPC registration occurred; thus, that activities, which not were completed according to the schedule, were registered. The selected case embraced the refurbishment of a top floor section at a hospital. The refurbishment project was carried out, while the hospital was fully functioning resulting in limited site access where materials only could arrive at early morning or late night. The site manager worked as a general contractor, the contract value was $5.5 million, and the contract period was 7 months.

The data collection consisted of on-site observations, participation in the follow-up process and the scheduling of the Weekly Work Plan, and semi- and unstructured interviews. The construction project was followed in a 6-week period with observation carried out once a week. During each observation round, on-site, unstructured interviews were carried out. The unstructured interviews served to help with the identification of root causes to non-completed activities. Moreover, a semi-structured interview was carried out with the site manager. The semi-structured interview focused on the applied construction control methods, including the application of Last Planner System, and the follow-up process.

3 Results

LPS was in general implemented successfully and functioned satisfactorily. An in-depth description to the application of LPS is listed in Table 1. Data to the application of LPS are gained through a combination of on-site observations and the semi-structured interview. The structure in Table 1 follows the structure of the LPS meetings starting with the follow-up process to last week's work. At the meetings, the general contractor was represented with a project manager, project engineer, and a superintendent. Moreover, foremen did represent the individual subcontractors.

3.1 Root Cause Analysis with Application of the 5 WHYs Technique

During the follow-up of last week's work, activities not completed according to schedule were identified and the percentage of planned activities completed (PPC) was calculated. It is important to realize that the PPC measurement is not a measurement of productivity but of schedule quality [14]. Thus, both activities completed too early and too late are registered. The registration of non-completed activities did not rigorously stick to the general procedure. Some activities were not registered as non-completions even though they were completed one day late or completed before schedule. Moreover, at the meeting, which takes place every Thursday, registration of activities being completed Friday and Saturday is based on estimates. Despite a number of non-completions have been overlooked and ignored, 17 non-completed activities were identified. Table 2 shows the 5 WHYs analysis applied to identify root causes to the 17 non-completions.

4 Discussion

Applying the 5 WHYs takes time and a lot of energy. One reason is that, when tracking down the root cause to the problem, the problem is changing hands. A lot of different sides and companies are involved and it can be difficult to get through

Table 1 Application of LPS

Step 1	Walk through the last week's work plan and registration of non-completed activities.	The individual contractor stated the completion state of the scheduled activities. Activities are registered as completed according to the schedule even though they are completed one day late or if the finish before scheduled. The scheduling meeting takes place at Thursdays. At the meeting, they are just guessing what work is completed Friday and Saturday. Calculation of PPC is carried out at the meeting.
Step 2	Scheduling of next week's work plan.	The individual contractor stated which activities he had scheduled to complete in next week (and the related Manning is noted). The task is scheduled in relation to the contractor and not in relation to where the tasks are located in the sequence (only very little discussion in the process). Often activities are recorded as a percent completion stage and not as completed tasks. Task was often very big resulting in only a few task on the weekly work plans Often the subcontractors were not very prepared. The activities are just scheduled—only rarely a discussion is taken place where the subcontractors in collaboration find an optimal sequence. But the subcontractors have the possibility to race questions and discuss. The schedule is not related to the weather forecast—even though there is some weather depended activities. Once the weather forecast was mentioned after the meeting. Only very rarely a workable backlog is registered.
Step 3	Update of the master schedule.	The update is basically done by the site manager. Though he asks the individual subcontractors about the status of the activities and the expected completions date. Looking into the coming activities. The site manager is trying to cut down the duration of the activities. Because they are delayed and wants to catch up. (Still delays so afterward he walks though only the critical tasks and tries to encourage the subcontractors to find activities which can be cut down so they can catch up.) Here, the sequence is continuously discussed in search for optimization.
Step 4	Update the constraint log.	Registration of the present constraints in activities which according to the master plan should be completed in the next week. (Should have been on the weekly work plan.) Registration of emerging and removed constraints.

Table 2 Applying the 5 WHYs technique to identify root causes

Repetitions	Problem observed	Why (1)	Why (2)	Why (3)	Why (4)	Why (5)
3	Roofing task not completed	Due to rainy weather	The roof was not covered.	It was on 13th floor, so the covering would need extra construction for handling wind. This was considered too expensive.		
	Vendor task not completed.	Our stuff is ready, but we are missing material.	We did not receive a delivery as expected.	The delivery lost their order (impact we will receive materials in 3 weeks).	No reason identified.	
	Material not present.	No reason identified.				
	Delivery of materials arrived too soon.	The subcontractor thought the task should be completed the following week (even though the plan said otherwise)	The subcontractors schedule did not match the projects master schedule	The subcontractor used his own schedule		
	Design not approved.	Activity put on weekly work plan still with constraint.	Architect promised to provide the information Monday—but it did not happen.	No reason identified.		
	Roof task not completed due to weather.	Thought it was going to rain, so we did not start the roof demolition.	Weather prognoses (very strange because it was very nice weather all week).	Weather prognoses were incorrect.		
3	Incorrect time estimate.	No particular reason it just to longer than expected to begin with.				

(continued)

Table 2 (continued)

Repetitions	Problem observed	Why (1)	Why (2)	Why (3)	Why (4)	Why (5)
	Incorrect time estimate.	Problems with work space.	Interruptions, people working, and materials in the way.	Did not foresee the others work and did not move their stocked materials.	They was not informed that the stocked materials should have been moved (the problem was solved at the following meeting where the activity was rescheduled in next week's work plan.)	
	Incorrect time estimate.	Material stock at the roof (fans) is slowing down the production because the work space is limited.	The fans are not moved down from the roof because there will not be enough space to move it up again after the present task is completed.			
3	Prior work not completed.	Time estimate of prior activity was incorrect.				
	Man power not present.	The subcontractor which was supposed to meet newer showed up.	No reason identified. The activity is rescheduled to Friday.			

to the person responsible, especially if the person responsible never is present on-site. This difficulty in identifying the responsible person has been the reason that it not always has been possible to identify the root causes. It is important to note that root cause identification would be easier at a factory production where all is working in the same organization. In the following, it will be discussed what lessons can be learned from the ones identified.

The 17 non-completions are categorized into 10 categories corresponding to Lindhard and Wandahl [15] nine preconditions plus an unidentified category. The result is as follows: Climate (4), safety (0), known conditions (0), materials (3), design and management (1), space (2), prior work (3), workers (1), heavy equipment (0), and unidentified (3).

No root causes were in the 17 incidents found to be related to the three categories: safety, known conditions, and heavy equipment. Since no heavy equipment was applied at the refurbishment project, it is not a surprise that no non-completions are related to heavy equipment. If the complete construction project had been followed and more non-completions registered, it will have been likely that some would have been related to safety and known conditions. Conversations with the project participants made it clear that the project had been redesigned due to unknown conditions where changes in internal and bearing element were made and not registered on the original drawings.

4.1 Climate

The climate in which the construction project takes place affects the work flow on-site. For instance, temperature, wind, moisture, rain, snow, waves, and visibility can influence the work conducted [16].

The climate is difficult to forecast. Unexpected climate conditions are difficult to handle. In one incident, an incorrect weather prognosis did cause the non-completion of an activity.

Climate precautions can in some cases prevent non-completions due to bad weather in evolving, but it is a management decision whether or not they should be implemented. This decision is often based on a risk and a cost and benefit analysis. In the construction project, one particular climate precaution was considered to expensive resulting in three registered non-completions. In a cost–benefit analysis, it is important to include the costs of these non-completions.

4.2 Materials

The material flow is complex; numerous of different materials have to be delivered to the correct work task on time [16]. To avoid re-handling or due to minimal storing capacity, a lot of materials are delivered just-in-time. This increases risk of non-presents, and moreover, the constraint is discovered very late without time to make adjustments in the schedule. This is also the reason that the lost delivery and the non-present material lead to non-completed activities.

The non-completion caused by a subcontractor following his own schedule is a repeatedly problem [17]. A construction project consists of multiple competing subcontractors, which have a tendency to work not only for the project but also for oneself [17].

4.3 Design

The construction design is defining which activities have to take place on-site and includes relevant drawings and task specifications. Thus, before an activity can start, the construction design has to be decided. In one incident, a missing approval from the architect leads to a non-completion. Even though no root cause has been identified, the non-completion still shows the risk of including "at risk" activities in the buffer [18].

4.4 Space

In construction, a great number of work activities have to be completed simultaneously with only limited space available [19]. Furthermore, a small miscommunication can cause unforeseen complications and lead to non-completions. This makes space allocation both complex and important.

4.5 Prior Work

Due to interrelationships between activities, the completion of the scheduled activities might depend on the completion of previous activities. Three non-completions have been caused by uncompleted previous work due to incorrect or misjudged time estimates. Despite no root causes have been identified, the lesson learned is once again the risk of including "at risk" activities in the buffer [18] and the importance of following the production to identify the misjudgments.

4.6 Workers

The completion of every task is dependent on qualified labor. In one incident, the subcontractor did not show up as scheduled which caused the planned task not to be completed on schedule. The actual reason was not identified, but no illness was reported to management. The reason could be caused miscommunication or once again it could be caused by a subcontractor working toward own priorities.

5 Conclusion

It can be very difficult to avoid non-completions. Only small miscommunications, carelessness, or misjudgments resulted in non-completed activities.

Increased collaboration and communication does reduce misunderstandings [20]. Communication on-site could be strengthened by introducing a Communication Schedule that contains interrelationships and bonds among the activities, the needs for coordination, and the one responsible [21].

Non-completions caused by carelessness can be reduced by increasing focus on the risks an activity is carrying. Thus, if the soundness of an activity is depending on the completion of prior work, material deliveries, etc.

Misjudgments are difficult to avoid, but the effect can be reduced by following the production to identify variations in work flow and to reveal time to make changes in the schedules.

The findings are transferable to a mass-customized production. Thus, the focus on communication and collaboration should increase as the level of customized orders increases. Moreover, the 5 WHYs technique can also be used directly as a learning technique in a mass-customized production.

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Challenges in Request Management: Demand Management of Customer-Driven Product Development

Anita Friis Sommer

Abstract Request management (RQM) is a new term used for managing customer requests for new products. It is the counterpart to typical product development processes, which has no direct customer involvement. It is essential to manage customer requests in a structured and efficient way to obtain profitability. This research study seeks to investigate the challenges of RQM in practice. Existing demand chain management literature is used as a basis for developing a RQM framework. RQM is investigated through an explorative research design in a dyadic B2B case study including a global industrial company and its customers. The study provides an insight into a new area of supply chain management, including the process activity flow and challenges involved across the process. Furthermore, the method is dyadic including the customer in the case study, which is rare in related research.

Keywords Customer request management · Demand chain management · Customer-driven product development · Dyadic case study · Customer integration

1 Introduction

Research within supply chain management (SCM) has evolved from logistics research by incorporating the view of managing business processes from raw material to end customer from a focal company in the supply chain [1, 2]. The next evolutionary step of understanding is demand chain management in which the focus is shifted from supply to a demand view, with the customer as the focal point rather than the company [3–5]. In competitive markets, it is essential for a supply

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chain to have a short-time and efficient response to market changes [6]. It is also essential to keep introducing new competitive products and to keep at pace with the change rate in the marketplace [7]. Managing customer requests for new products is viewed as special instance of demand chain management, which has so far not been investigated in SCM research. Traditionally, new product development has been viewed as a process initiated by the focal company, when in fact there are various examples of product development being driven by customer requests [8–11]. This research study is concerned with B2B mass producers where customer requests for new products can be used to feed into an existing product portfolio. Request management (RQM) is managing new product requests from customers. In this paper, the phenomenon is investigated from a demand chain management perspective and the objective is to understand how companies can develop competitive advantage and increase customer value by managing customer requests for new products and to develop an understanding of the complexity of the cross-organizational process. The objective raises the research question: *What are the elements and structures of the request management process, and what are the challenges involved?*

First, a theoretical background is presented, including frameworks and models necessary for investigating the phenomenon in practice. Afterwards, the method is presented followed by analysis and results of the research study. Finally, the results and contributions are discussed, including a presentation of a first take on a generative model of the RQM process.

2 Theoretical Background

Recently, it has been proposed that managing the demand chain can be viewed as a separate discipline involving both logistics and marketing management [4, 5, 12]. The definition of DCM used in this paper is that demand chain management is: understanding and integration of customer value as the focal point in key business processes throughout the supply chain. DCM has been identified as a cross-managerial challenge involving marketing and supply chain management in interaction with the market [12]. DCM is combining the managerial areas of marketing and logistics for increased competitiveness. Most companies today do not have this integration, but some in highly competitive markets have recently started to coordinate across these traditional managerial boundaries [12]. Another framework on DCM developed by Jüttner et al. [13] presents a similar collaboration between marketing and supply chain managers. This framework is differently focused on the managerial factors of the focal company and has not included the market as a factor. Instead, the factors identified for DCM are managing the integrated processes between demand and supply, the structure between the processes and customer segments and social interaction between the marketing and SCM. Both frameworks on DCM seem to include relevant elements. The framework by Jüttner et al. [13] is developed through workshops with marketing and

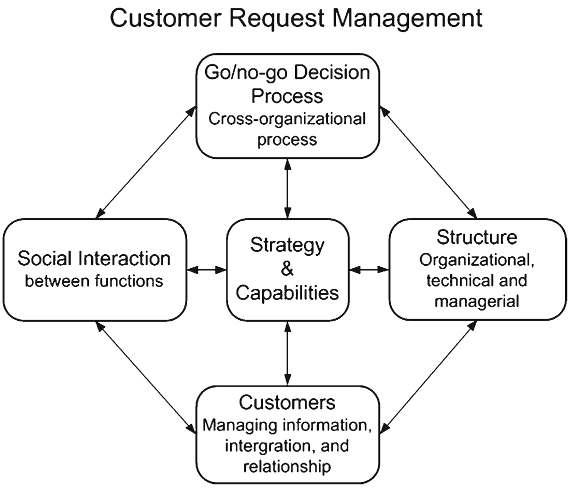

Fig. 1 Customer request management framework

SCM representatives, whereas the framework by Hilletofth et al. [12] is developed through the researches own reasoning based on previous research. The special instance of DCM where the supplier manages customers request for new product or product changes rather than existing products is termed RQM. Based on DCM literature, the framework depicted in Fig. 1 is used for exploring RQM.

2.1 Request Management Process and Challenges

Request management is closely interrelated with collaborative product development. Collaborative product development has been widely investigated in existing supply chain management literature [7, 13–17]. In existing literature, there is a lack of research concerning the supplier's side of B2B collaborative product development where the initiator is customer requests for new products [18]. From the supplier's side, this consists of two elements: request management and collaborative product development. RQM is defined as managing incoming customer requests for new products from new and existing customers including a go/no-go decision process. The accepted product requests developed in collaboration with the customer, and thus, the second element in customer-driven product development is collaborative product development. RQM is a cross-functional supply chain management business process like demand management and product development [2], and therefore, RQM is being viewed from a SCM perspective.

Customer requests for new products, which is customers acting on their needs by a request to a supplier, are viewed as unfixed and to some extend variables of external influence and are not regarded as final expressions of fixed needs. This view is supported by Bonner [19] proposing a view on collaborative product innovation as a learning process. When customers are actively engaged in collaborative product development, they are affected through interaction with the supplier through learning in a joint problem-solving project. In particular, when dealing with ‘hard-to-articulate’ knowledge collaborative approach is relevant to apply, the first assessment of customer needs is likely to be insufficient. When customers engage in collaborative product development, it will have a positive effect on customer commitment and loyalty [19]. Quantitative research studies have also indicated a significant relation between customer involvement in NPD and market success/performance [20, 21]. Following this line of thinking, it is relevant to use customer requests to actively include customers in new product development, thereby improving commitment and loyalty from the specific customer, but also to improve general market success.

3 Method

Exploratory research requires an in-depth understanding of the phenomenon in question. Therefore, we apply the case study method to explore a specific instance of the phenomenon in question [22]. A case study is ‘an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context’ [23]. In order to create visibility of the research process, it has been chosen to present each method step including sampling, data collection and data processing and critically evaluate the quality of the applied research design. This paper includes a single dyadic case study. The dyad is between a buyer and supplier with focus on investigating the challenges involved in the cross-organizational RQM process initiated by the customer but managed by the supplying company. The chosen case company is a global industrial production company with more than 30,000 employees worldwide. The company’s markets are within thermodynamics, including a large range of products like valves, air-conditioners, and thermostats. The specific business unit, which is chosen for this research study, produces high-quality industrial thermodynamic products to B2B manufacturing customers. This business unit was selected because it is currently receiving an increasing amount of customer requests for new products and has started to focus on improving the managerial tasks involved with RQM. The business unit has a number of large original equipment manufacturer (OEM) customers, and the primary sales strategy is to develop long-term relationships with customers through close interaction, high-quality products and services. The customers are one medium and one large industrial OEM company both with a long history in collaborating with the focal company. Both have recently been requesting for new product development at the supplier and have had successful outcome of following joint product development projects.

The organizational functions of interest for the RQM process was identified through a preliminary study including two times 1 h interviews with the project manager in charge of improving the RQM process. The RQM process was found to be a cross-functional business process, which cuts across the operations

Table 1 Overview of interview study

Functions	Operations and RQM manager	Engineering	Technical service	Strategic sales	Sales	Customer
Single interviews	2	2	3	2	3	2
Group interviews	2		2		2	

department including technical service, engineering, and department managers, and the sales department including management, coordination, and sales representatives from local sales departments. Persons from all participating functions in the RQM process have been interviewed. In total, 12 interviews on 1–2 h were conducted across the internal RQM process including two cross-departmental group interviews both lasting about 2 h. Furthermore, the project manager improving RQM was interviewed 6 times for 1 h over a six-month period to follow the progression of the improvement project. Additionally, two OEM customers were interviewed each for 1 h. The interviews were in both cases conducted with the employee who had been responsible for the primary contact to the supplier during the RQM process. The contact to the customer was made through the sales department manager of the supplying company. An overview of the interviews is provided in Table 1.

The interview study was based on a semi-structured interview guide constructed to explore the RQM challenges based on the elements in the RQM framework. All interviews were recorded, and during each interview, notes were made. Afterwards, all audio recordings were compared with the notes, which were used during the analysis. The interviews were supported by unobtrusive data from the company, including power points, e-mail threads and documents with formal information concerning the process. To increase validity of the study, triangulation of data was applied whenever possible [23]. Furthermore, the analysis and outcome were presented and discussed with the operations manager, sales manager and the RQM project manager, thereby increasing data reliability. Internal validity and reliability of the research study is perceived to be high due to the depth of insight into the company and triangulation of data [22].

4 Analysis and Results

The company analyses the amount of accepted customer requests resulting in a final sale, called hit-rate. Ideally, this number should be 100 %, since all accepted requests should lead to sold products. However, the hit-rate is only about 60 % meaning that 40 % of the developed products are never sold. Evidently somewhere in the process, something is very wrong. An overview process model of the RQM process is been developed by the technical service (TS) department in an attempt to formalize the RQM process. The process model is a stage-gate model, which includes a linear flow from an enquiry stage to an attractiveness evaluation stage. The two stages consist of the following steps:

Enquiry Stage

1. A customer enquires for a new product or product change to a local sales employee.
2. The sales employee fills out a customer request sheet (CRS), if the enquiry is considered profitable. When in doubt of business potential, TS is contacted informally.
3. The CRS is forwarded to a regional strategic sales development (SSD) manager. Requests that are outside the range of the company's strategy or have a too low business potential are rejected. Otherwise, the CRS is forwarded to TS. Often the CRS details are unclear and SSD contacts the sales employee for further details, which are then requested from the customers.

Attractiveness Evaluation Stage

1. Technical service receives the CRS. CRSs are distributed to two different TS departments depending on the product area and specific TS managers within the department according to global regions. For instance, a TS manager is responsible for sensor products in the North and South American regions.
2. Each TS manager is responsible for a go/no-go decision for each CRS, which is based on a cost–benefit analysis. TS managers use the engineering department as support function during the analysis. The engineering department is in close contact with production managers to ensure that the product design fit production capabilities. Often, the sales employee is contacted by TS to elaborate on CRS specifications. The sales employee then contacts the customer in order to specify their needs.
3. After a number of iteration cycles involving the customer, sales employee, SSD manager, TS manager, engineering employees and production managers, the TS manager has collected enough data to make the final go/no-go decision. The customer request is then formally accepted or declined with a specific reason attached, and the process proceeds to collaborative product development.

Event though the stage-gate model is the formal representation of the RQM process, the model is inconsistent with the actual activity flow and is therefore not used consistently. The two stages are assigned to the departments of sales and TS, yet all stakeholder departments often participate in the process more than once during the process flow in each stage. Instead of the linear flow, the process has an iterative activity flow across the two stages and across two distinct organizational silos, which include sales and SSD in one silo, and the operations department (TS, engineering and production) in the other silo. The process iterations are considered necessary to reach a sufficient foundation for the go/no-go decision in the current set-up, but they are not used consistently or formally, and therefore, the iterations are hidden underneath the formal RQM process.

Table 2 Overview of challenges in RQM

RQM challenges	Operations manager	RQM manager	Engineering	Technical service	Strategic sales	Sales	Customer
Lack of knowledge sharing		X	X	X	X	X	
Uncertainty in go/no-go decision		X	X	X	X	X	
Long lead-times	X	X	X	X	X	X	X
Unclear strategy		X	X	X	X	X	
Increasing amount of requests	X	X		X			

4.1 *Request Management Challenges*

Five major challenges are identified in the RQM process, which are related to the low hit-rate. These include lack of knowledge sharing, uncertainty in go/no-go decision, long lead-times, unclear strategy and increasing amount of requests. Table 2 includes an overview of the five major RQM challenges, and the stakeholder groups that identifies the challenges, which will afterwards be described in more detail.

Lack of knowledge sharing Local sales employees refer to the operations unit as ‘a black hole’. As one employee states: *‘You send the CRS in, just to check if it is possible to produce this item, and hear nothing for months and suddenly they send you an email that the product is now ready to be sold’*. This is one of the more extreme statements, yet employees generally find a lack of knowledge sharing to be challenging especially between the two organizational silos. The lack of knowledge sharing increases iterations and increases lead-time.

Uncertainty in go/no-go decision The go/no-go decision has a high level of uncertainty related especially to tree interdependent factors: Finding the optimal technical solution, estimating production costs, and estimating market potential and customer value. Uncertainty is generated from the interdependencies, since for instance both costs and benefits are linked to the chosen technical solution, and thus, if the solution is altered by engineering or the customer, it affects the entire analysis. Furthermore, the technical solution cannot be developed solely by the engineering department due to the high level of technical complexity, which requires additional input from the customer. Hence, these alterations change the prerequisites for the go/no-go decision even at late stages of the RQM process and during the following product development process. Thus, as a TS manager describes it: *‘The go/no-go decision is nothing more than a qualified estimate… We often want to reply that we definitely maybe will accept the request’*.

Long lead-times Through the analysis, it was found that managing even simple product requests take weeks and even months. Questions about technical requirements and possible price per unit are not simple to answer and in many cases generate counter questions, thus going back and forth in the organizational structure. TS and sales employees express that many requests are so to speak '*lost in translation*'. They express a need to develop an overview system of the requests and a more structured managing process internally in their department.

Unclear strategies All internal interviewees, apart from operations management, express that they do not have sufficient knowledge on the strategy and capabilities of the company. They explain that so far, there has not been a clear-cut product or market strategy, which has had the consequence that neither capabilities nor the strategy has been considered in the RQM process until now. Operations management has now, after becoming aware of this problem, initiated a market strategy development programme to meet this challenge and considers developing a technology centre function to share knowledge of production capabilities.

Increasing amount of requests Finally, during the last years, the company has experienced an increasing amount of requests from all over the world. The challenge is to keep up with the pace of responding to all requests in a timely manner while maintaining improving the quality of the RQM process. So far, there have not been any internal initiatives to solve this problem, and TS managers express that they are increasingly pressed by a larger list of unfinished CRSs.

5 Discussion and Conclusion

During the analysis, the process flow across stages and organizational structures was identified including a set of major challenges affecting the RQM process negatively.

This study indicates that mass producers in B2B relationships receive requests for new products and product changes and that RQM is an important management discipline that may increase customer value and be an important competitive advantage in increasingly demanding markets. Indeed, there has been found strong indications from other research studies of positive outcomes of collaborative product development increasing customer value [24–26].

The RQM process contains a high level of complexity including several interdependent factors involving several disconnected stakeholders, product and production technology, market potential in relation to existing products, customer relationship. Hence, the challenges might be symptoms that the process is not managed as a complex development process but rather as a demand management process with low uncertainty. RQM differs from DCM on all five elements of the framework. In DCM, the go/no-go decision process is normally related to production capabilities and lead-time on existing products [1]. Hence, the decision process of RQM is of a different nature, than the one typically managed by mass producers. Social interaction in DCM is complex, yet for RQM the complexity is increased further by including changes in the product itself, which requires inclusion of additional functions in the process. The structure supporting the RQM process is similar to that of DCM in the case. Yet, the RQM process complexity seems to require a more flexible structure, with close interaction between stakeholders. The customer is an active part of the RQM process, whereas they are merely the initiator of the DCM process. Finally, strategy and capabilities of RQM differs from DCM in the type of strategy, i.e. new product strategies versus market strategies, and capabilities of product development and project management rather than demand management. Hence, we conclude that RQM even viewed as a special instance of DCM is a fundamentally different process both in regard to complexity, customer involvement, activity flow, and business potential. Even so, both RQM and DCM are customer-focused processes, which must be viewed as parallel, sometimes even dependent, processes that greatly affect the perceived customer value. The research study is limited in that it is only concerned with the RQM process, and thus, new product development, production management, and logistics management have been omitted from the study. The supply chain for the product is considered relevant [14, 27], and therefore, we call for further studies on the relation between RQM and supply chain management.

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Customization Issues: A Four-Level Customization Model

Kaj A. Joergensen, Thomas D. Brunoe, Stig Taps and Kjeld Nielsen

Abstract Implementation of mass customization and product configuration in companies requires fundamental considerations about how products can fulfil the demand from customers. In order to support such decision-making, a multi-level model for customization is developed. This model identifies four different levels of customization, ranging from the structure level at the bottom, through the performance level and the experience level, to the learning level at the top. The model also has a dual view with customers/demand at one side and product/supplier at the other side. It is a rather general model, which can be applied to many types of products, and typically, product designers must decide how far up in levels the customization should aim. In this paper, the four-level customization model is applied to wheel chairs.

Keywords Customization · Mass customization · Product configuration · Solution space development

1 Introduction

Mass customization (MC) was originally introduced by Davis [4] and Pine [16, 17], and several companies have recognized the need for mass customization. MC has set focus on new requirements regarding the view of customer–product relationships and much effort has been put into identifying, which success factors are critical for an MC implementation and how different types of companies may benefit from it [1, 7, 14, 20, 22].

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For obvious reasons, there are different strategies on how to implement MC most appropriately and it varies naturally between different companies, markets and products. Because there is not a single generic strategy, it is important to look at the issue from different viewpoints. The fact that products must be easily customizable in order to achieve MC has been described comprehensively in the literature, and more general, [1, 16] have discussed the issues related to readiness of the value chain. Newer research underlines that MC is a strategic and sometimes non-reversible development and suggests that the change process is considered as a strategic mechanism. Consequently, in order to benefit from MC, the mangers must tailor the development process to the existing business, rather than vice versa [21].

Customization is very often an important issue regarding design, marketing, sales and production. It is rather fundamental for customers to seek for individual demands, and consequently, suppliers must decide to what degree they want to fulfil these demands. Many manufacturers have learned that manufacturing of many product variants may increase the cost dramatically and non-profitably.

2 Product Configuration and Mass Customization

An often used approach for implementation of MC is product configuration, in which a series of products is defined by one single model—a product family model [10]. Hence, a product family can be viewed as the set of end products, which can be formed by using a predefined product family model. The result of each configuration will be a model of the configured product (configured product model) and from this model, the physical product can be produced.

Most of the methods, which exist for product family modelling, focus on modelling of the solution space [21] of a configuration process. This means that they describe the attributes of the products and the product structure. Hence, they do typically not focus on additional information, which goes beyond what must be used to perform the configuration itself. This kind of information, which could include customer, market, logistics and manufacturing information, is according to [19] similarly important, since a successful implementation of MC must integrate all information flows.

A product family model is often the basis for development of a product configurator, i.e. a tool, computer software, which can support users in the configuration process [6]. Product configurators are important tools, which can provide a range of opportunities for adding new dimensions to the subject and configuration may also add more value to customers. Therefore, when a configurator is designed, a large number of design parameters must be considered and balanced decisions must be made.

Mass customization and product configuration are relevant for many enterprises and great benefits are normally found, where customization is common and where the idea is introduced gradually. In general, however, the benefits depend very much on the product and the market. In the relationship between the manufacturer and the market or more precisely the product and the customer, the product configurator plays a major role.

A major distinction between markets and customers is business-to-business (B2B) and business-to-consumers (B2C), and an important dimension here is the degree of personalization. Personalization is most relevant in relationship with B2C and a high degree of personalization towards individual customers or small groups of customers generates special requirements to product configurators, but, on the other hand, this also raises new opportunities for increased market share.

The enormous development of electronics and particularly computer-based technologies has resulted in great change in product design and product development. For instance, a large range of products has shifted from mechanical products to mechatronic products with electromechanic and electric parts [2, 3]. This development is continuing, and for many new generations of existing products, the percentage of traditional mechanical parts are decreasing. Particularly, customization of mechatronic and electronic products raises new issues.

3 Customization Levels

In order to support the decision-making regarding customization of products, a model for customization has been developed [11, 12, 13]. This model (see Fig. 1) identifies four different levels of customization, ranging from the structure level at the bottom, through the performance level and the experience level, to the learning level at to top. The model has a dual view with customers/demand at one side and product/supplier at the other side. It is considered a general model, which can be applied to many types of product families, and typically, it must be decided how far up in levels the development should aim. Further, a good match between the two sides and on each level must be established.

In the following, the four levels of the model are described in further detail and some most typical design issues are addressed and explained by referring to wheel chairs as a sample product family (see e.g. Fig. 2). Obviously, wheel chairs must be manufactured in many variants to meet the demands from a great variety of end-users. Hence, the degree of personalization is rather high for this product family. In the following, the product/supplier side of the customization model has the primary focus and customer/market demands rest only on commonly known end-user requirements and are not addressed in particular.

3.1 Customization: Structure Level

It is very common to view customization on the structure level because it is characterized as a matter of offering components, which can be used as building blocks. Typical commercial product examples are computers, automobiles and

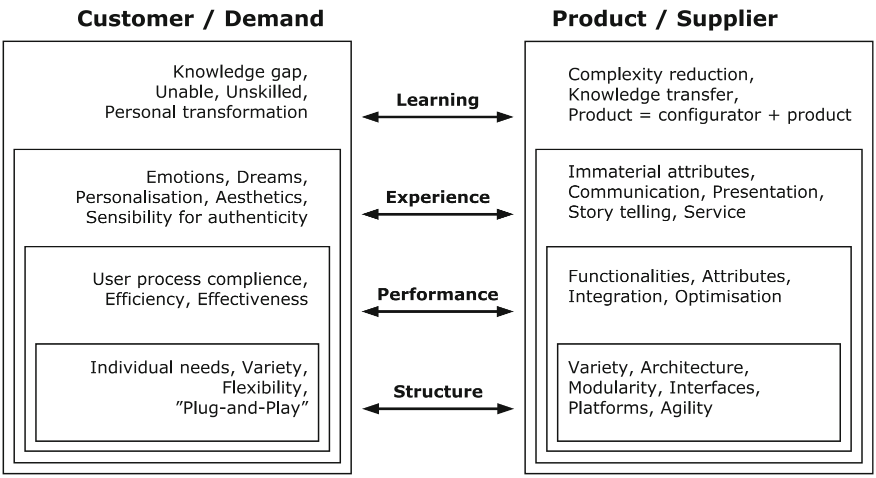

Fig. 1 Customization on four different levels

Fig. 2 Sample wheel chair

bicycles. Important issues are modularity, interfaces of modules and product platforms, i.e. end products are configured by selections among modules, and modules are assemblies of components. Very often, modularity is recommended as an enabler for implementation of product configuration, and modules are most preferably identified with clear separation of functionalities, i.e. modularity is in contrast to integration. Further, different architectures of modularity are worth considering.

Looking at wheel chairs on the structure level comprises the identification of components: frame, wheels, seat, footrest, bearings, brakes, etc. The end product is an assembly of these components, and a traditional consideration, seen from a manufacturing point of view, is to decide which components are standard sub-supplied components and which are manufactured in-house. This issue must be viewed closely connected to the need for customization, where nearly all components must be available in multiple variants depending on, e.g., the size and weight of the end-user. The frame, for instance, must be provided in different sizes (height, width and depth) and strength. In addition, wheels (main wheels and front wheels) and seats must also be offered in different variants.

Consequently, a wheel chair is a product family and the frame is a good representative of the classic dilemma of MC: to provide a large range of variants for customers versus to constrain the number of manufactured variants. Typically, this problem is solved by modularization, and for this product family, the frame will become the primary module. For this module, it is important to focus on all relationships with the remaining components and design interfaces, which are standardized and easy to assemble. Further, when the product family is presented to customers and the foundation for configuration is build, other modules are identified in order to simplify choice navigation. A typical result here is that multiple components are put together in one module, e.g., the two main wheels are together a module and likewise the two front wheels.

The frame module is special because it is also configurable and particular relationships with the remaining modules and components can be defined. Hence, measurements of the end-user may constrain the configuration of the frame, and the frame may constrain the selection of other modules/components. A configurator model of the frame has special importance and become a key instrument to get success regarding implementation of MC.

3.2 Customization: Performance Level

On the next level, the performance of products is essential. When products are installed in their user environment, they perform their functions—hopefully in the expected way. Therefore, considerations about the ability to perform the functions, which are required by the customer, are very important and should be a significant subject of configuration. Hence, the focus of product configuration is shifted to identification and definition of product attributes instead of modules and components. This is particularly important, when the performance of the product is essential and a careful balance between integration and modularization must be established. Extreme product examples are automobile engines and computer processors.

Functional issues of products are important in relationship with modularization and mapping of functional requirements to specific modules is considered in [9, 5, 15]. Jiao proposes to use a triple-view representation scheme. The three views are the functional, technical and structural views. The functional view is used to describe, typically, the customer's functional requirements, and the technical view is used to describe the design parameters in the physical domain. The structural view, which corresponds to the structural level described above, includes the mapping between the functional and technical view as well as the rules of how a product may be configured. The description of this modelling approach is however rather conceptual and is not easily implemented in industrial applications.

The performance of a wheel chair is very important for the end-user. Performance requirements must be specified in harmony with the end-user and is about, e.g., seat and footrest adjustment, stability and manoeuvrability. For instance, ideal stability must be arranged individually by positioning the seat and thereby gain the right balance of weight between main wheels and front wheels. This performance requirement leads to further design constraints on the frame in addition to those identified on the structure level.

The two lower levels of customization, the structure level and the performance level, are rather common and widely used with many products and on all types of markets. The additional two upper levels of the customization model will primarily relate to customers and products with higher degree of personalization.

3.3 Customization: Experience Level

The next level, termed the experience level, focuses on special attributes of products and on immaterial attributes, which are related to customer's emotions and even dreams. Involvement in a configuration process will for many customers result in a higher degree of satisfaction, and the customer will likely feel a stronger attachment to the solution [18]. The experience level of customization is therefore strongly related to personalization. Hence, customers typical for this level are primarily individual persons or relatively small groups. Many fashion and service products, for instance, are highly personalized and aim at giving the customer-specific experiences. Additional examples are entertainment, personal care, wellness and travel. Many examples show that configurators for these types of products aim at special values of the products for the customers. Also with ordinary products, many customers may find extra dimensions of personal value. Customer's concern for the environment may for instance give more preference for ecologic products.

A major distinction regarding markets/customers is the personalization dimension. Obviously, personalization is most relevant in relationship with business-to-consumer products and a high degree of personalization towards individual customers or small groups of customers generates special requirements to products, but, on the other hand, this also raises new opportunities for increased volume. Products may offer user-driven customization, and also this way increases the emotional-based satisfaction. In order to create good support for the experience level, it is important that the available options are matched properly with the customer needs and it is important to analyse, what effect different attributes have on customers, whether they are real or imaginary attributes.

An important aspect of this customization level is authenticity. Gilmore and Pine [8] show that customers are becoming more sensitive and expect higher and higher quality of goods and services. Practically all consumers desire authenticity. Every person is unique, and he is perhaps aware of his own uniqueness and values it. The consumer sensibility for authenticity evidences itself, and whenever informed, individuals independently purchase any item with which they are intensely involved. According to this theory, many companies fail if they act against their own policies. If a company claims to be very conscientious, it may very fast loose loyalty, if the opposite is found; for instance, if it is disclosed that some products are produced by children and perhaps under poor circumstances. These aspects relate also to product configuration. Because of the endless number of emotional preferences residing at customers, this customization level could be more beneficial and should get more attention.

For the wheel chair product family, the experience level is also very important. There are many ways, how end-users can be satisfied emotionally. For instance, seats can be formed differently and, thereby, give different seating comfort. Some basic comfort parameters may relate to the performance level, but additional ergonomic efforts may also be valued, especially for end-users who have to use the wheel chair for long periods. The colour of the wheel chair may also be an important opportunity for giving the customer a special experience from using the product.

Means for good configurator support on the experience customization level are to present the perhaps unseen values of products, to provide good and reliable guidance to the user and to display consequences of choices. If the options are limited, it is important to be selective regarding customer segments. However, some customers may be intimidated by getting a wrong message.

3.4 Customization: Learning Level

At the top level of customization, the learning level, special services must be offered that may result in further impact on the involved customer or end-user. A product in the traditional understanding may be present, but special aspects of the product may lead to a learning process for the customer/end-user. Often, this is related to complex products with numerous functionalities, which require substantial training and support for optimal usage. Many services of this kind can be provided by related Web sites with user-friendly tutorials and help support and assistance for troubleshooting.

A large amount of features and services may be included in products and such services may identify a range of subjects that represent a gap between the customer's knowledge and what the product can offer. Consequently, the transformation of the customer is a key issue on the learning level.

The product may be difficult to understand for the customer, and the knowledge gap may be related to different aspects of the product. Perhaps the product must fit into complex processes at the end-user's site, and it may be difficult for the customer to estimate, how the product can fulfil the requirements. Maybe the customer for the first time is engaged in a complex purchasing process, where many issues are new to the customer. Therefore, it should be possible for the customer to find answers to questions about such issues. If customers are unable or unskilled to make decisions about such issues, trustworthy guidance must be provided, perhaps along with the configurator. In this way, the configurator and guide are integrated with the product or it can be seen to complement the product.

The learning level can also be related to wheel chairs. End-users may have many different usages and may require different set-up of their product. However, an optimal set-up may be difficult to find. As already mentioned, stability is an important issue for wheel chairs and a good balance for an end-user may be violating requirements about stability. Very often, an experienced consultant is needed to find the solutions. This person may know a method for doing so, but, if such a method must be described and applied to a wide range of use cases and proportions of end-users, it may become very complicated. To develop such an amendment to the physical product may initiate a valuable learning process for the end-user.

Like for the previously presented customization levels, issues on the learning level should create further attraction from the customer towards the product but adding such additional features also requires a precise segmentation of customers in order to attract the attention and initiate a relationship with new customers. Too many features may give a negative effect and well-skilled customers for instance may find this kind of support as a barrier, so it is important that the configurator is able to adjust itself to different customer types.

4 Conclusion

If product design is performed with respect to mass customization, customization issues are normally very important to consider and, in order to support this, a model for customization has been developed and presented. The model arranges customization in four different levels of customization, ranging from a structure level at the bottom, through a performance level and an experience level, to a learning level at the top. Further, the levels must be seen from both a customer/ demand side and a product/supplier side. Designers must consider to which extend the issues related to the four customization levels should be applied.

In addition, it is important to create a design approach, which includes both a bottom-up view and a top-down view. The presentation and the select issues related to the wheel chair product family clearly underline it is not enough to look at the structure level, which is the most commonly used view. Each of the levels above also contributes with special views of customization and design requirements identified on one level have influence on other levels. Hence, a good balance among the use of all levels is preferable.

An important dimension of customization is the degree of personalization because a strong orientation towards individual customers or small groups of customers generates special requirements regarding customization. Implementation of such requirements, however, may also raise new opportunities for increased volume. In connection with the presentation of the customization levels, a wheel chair is introduced as a sample product family. Obviously, this is a type of product, which must be personalized to a rather high degree. It must be underlined, however, that the customization model can be applied to many other types of products and many markets or customers.

Many applications of configuration and use of computer-based configurators provide a range of opportunities for adding new dimensions, and it is argued that the presented model for customization on different levels can add more value to a product and make it more attractive for customers.

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Danish Public Construction Counselling Selection and Assignment Criteria in European Tendering

Jesper Kranker Larsen, Lene Faber Ussing and Thomas D. Brunoe

Abstract One of the largest customers in the Danish construction industry is public agencies that own and develop projects. For some of the counselling services, they recur to be put out in European tendering. The aim is to find which selection and assignment criteria are used most in public tendering. How projects use selection and assignment criteria for counselling services and finally if there is significant use of selection and assignment methods in public counselling. The method is based on 74 public counselling tenders from the European Tenders Electronic Daily database from January 2010 to March 2013. A following standard error and Fisher's exact test were conducted to test if there were any significant relations. Results indicate that invited tender with pre-qualification and most economically advantageous offer in 57.1 % of the tenders are the most used selection and assignment criteria in public counselling services.

Keywords Assignment criteria · Construction project management · Public counselling projects · Selection criteria

1 Introduction

Today, nearly all public and private construction projects and related counselling services are through a bidding round before the design stage and following construction stage; during the bidding round, different selection and assignment

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criteria are used to secure that the project partners have the right competence and resources according to the chosen selection and assignment criteria for the project in tender [1]. The different combinations of selection and assignment criteria are therefore used to secure the best offer according to the project economy, user demands and the owner and project manager's strategic project plan [2].

Normally seen selection criteria in the Danish construction industry are invited tender with a pre-qualification process where the pre-qualification process requires that the incoming offer has the right competence and resources to fulfil the project's demands to both technical and human capital etc. Another normally used selection criteria is open procedure tender where all offers are welcome, and no further qualification is required. Looking at the used assignment criteria, the lowest price is a normally seen criterion where the owner and project manager use the market forces to secure the lowest price on a project between the incoming offers. The obverse of that assignment criterion is a most economically advantageous offer where a planned percentages-weighting of parameters such as architecture, functionality and price is used to evaluate a more varied perspective to find the best offer for the specific project or task [3].

It is therefore of particular interest to study how public construction counselling services' selection and assignment criteria are used and combined within different project types such as restoration and maintenance projects', and new construction project types, based on the public construction agencies. These agencies are the largest owners and developers in the Danish construction industry, and their use of selection and assignment criteria in construction counselling services has never been studied.

The aim of this study is therefore to find out which selection and assignment criteria are mostly used in Danish public construction counselling services put out in European tender, how different types of construction projects use selection and assignment in the bidding process and finally, if there are any significant difference between the used selection and assignment methods in Danish public counselling construction projects.

2 Materials and Methods

The research method used for the study is based on a quantitative research approach in three stages to secure a systematic research process.

The first stage the "input stage" was conducted basically as a literature review according to [4] and adjusted according to [5, 6]. The authors started the research by first identifying which Danish public agencies manage, develop and supervise public construction projects and buildings, which hereafter was converted into search strings by adding "AND", "AU" and "CY" for example, CY = [DK] AND AU = [Agency no. 1] AND AU = [Agency no. 2] etc., and hereafter tested in the European Tenders Electronic Daily database to find which search string identified most tender cases. The search string that identified most tender cases was hereby the main search string, where 258 hits were identified, and by a following data-proceeding, the amount of cases was reduced, because some tender cases were construction tasks and others did not contain useful or correct data for a following data analysis.

During the next “processing stage”, the data were limited to focus on tender cases from January 2010 to the month of March 2013, where the final 74 cases were found and hereafter converted to numerical data so a following segmenting and data analysis was possible. The data analysis was conducted in the software Microsoft Excel, where the dataset was calculated for standard error and Fisher’s exact test of independence for testing if there was any significant use of selection and assignment criteria, the significance level was decided to 0.05 according to [7].

In the last “output stage”, the result was presented for colleagues for a final review, and hereafter the paper and arguments were constructed according to the results.

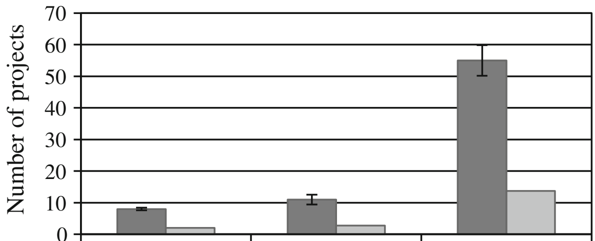
3 Results

In this section, the results from the third stage, output stage will be presented by a quantitative research approach to answer the outlined research questions, the findings of the analysis will be presented individually in selection and assignment criteria according to the specific counselling project types, and finally the selection and tendering criteria will be analysed using a Fisher’s exact test to find if there is any significant use of some criteria.

The different counselling project types are used in the analysis, and the results are shown in Fig. 1, where the segment “restoration and maintenance projects” by 8 (10.8 %) of the 74 cases covers construction counselling services, where the objectives are to restore and maintain older buildings, where its user requirements or user functions have changed so radically that a restoration of the building is required. Further, the described segment will also include small counselling services such as construction part replacements, for example windows, roof and other facility management counselling services that still demand a European tendering.

The second most involved project counselling services are “new construction projects” by 11 (14.9 %) of the 74 cases that contain construction counselling services of new buildings such as offices and university buildings etc.

The segment “unspecified counselling services”, which covers 55 (74.3 %) of the 74 cases, contains tenders where the selection or assignment criteria are described, but the specific construction counselling type, whether it is a new construction project or restoration project, is not described in the tender documents and the exact reason for the large amount of unspecified counselling services is the authors not familiar with, but a theory could be that the tender cases represent a phase in the construction project where it are in its client brief phase and where the specific project objective still is unclear.



	Restoration and maintenance projects	New construction projects	Unspecified counseling services
Number of project types	8	11	55
Yearly arithmetic mean between 2010 - 2013	2.0	2.8	13.8

Fig. 1 Counselling project types for all 74 cases with standard error

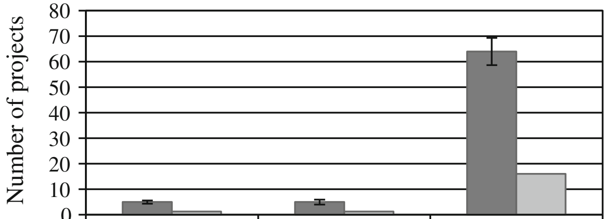
3.1 Selection Criteria

Looking at the most used selection criterion, regardless of counselling project type, it is invited tender with a pre-qualification process in the 64 (86.5 %) of the 74 cases used, see Fig. 2.

The advantages of invited tender with a pre-qualification process are that the owner and project manager can secure that the tenderer has the right qualification and resources to manage and design the project before the following offer process starts and hereby use the pre-qualification process as a control point to protect the project from counselling partners who do not have the qualification to fulfil the minimum requirements, which the owner and project manager have set as control points in the pre-qualification process.

Second most used selection criterion is found to be open procedure tendering by 5 (6.8 %) of the 74 cases which is also the level for the no published tendering segment at Fig. 2, which by looking at the distribution of the three segments not is distributed equally in the counseling services.

The advantages of using open procedure tender are the additional unlimited offers that, if it is an advantage for the case, can press the total project price, but by opening for in theory unlimited offers, the chance for frivolous counselling partners will also increase which potentially can give later project complications in the following project phases. Therefore, the open procedure tender has both advantages of using the marked forces to secure a large amount of offers and of pressing the total price, but on the other hand, the selection model has the weakness of increasing the chances for counselling partners who do not have the right competencies. Open procedure tender should therefore only be used in counselling tasks where the impact of later complications is limited to the general project and following construction process.



	No published data	Open procedure tender	Invited tender - pre-qualification process
Number of project	5	5	64
Yearly arithmetic mean between 2010 - 2013	1.3	1.3	16.0

Fig. 2 Selection criteria for all 74 cases with standard error

Table 1 Fisher's exact test for open and invited tenders compared to project types, 0.05 significance level

Null hypothesis $H_O : \mu 1 = \mu 2$: *Open procedure tender and invited tender are used equally between restoration and new construction projects?*

	Open procedure tender	Invited tender, pre-qualification process	Total row
Restoration and maintenance projects	0 (0.0 %)	3 (33.3 %)	3
New construction projects	1 (11.1 %)	5 (55.6 %)	6
Total column	1	8	$n = 9$
Fisher's exact test results			
Hyper geometric probability			$H_O : \mu 1 = \mu 2 : 0.6667$
Two-sided p value			1.0000
Probability $a \leq 0$			0.6667
Probability $a \geq 0$			1.0000

To test if there is a significant level of selection criteria between the different counselling project types, the null hypothesis is tested, see Table 1, where the null hypothesis was confirmed, and therefore. the data are not demonstrating a significant use of invited tender with a pre-qualification process, but by looking at Fig. 2, it is obviously by 86.5 % of the cases using that selection criterion. The Fisher's exact test is therefore not demonstrating a clear picture of the use of the selection criterion because on the data in most of the cases is incomplete on counselling type of the tender.

The results of the selection criterion must therefore be that there is an indication of significant use of invited tender with a pre-qualification, and by looking at the limited distribution between project counselling type, there is a tentative indication that both restoration and maintenance counselling services by 33.3 % and new construction project counselling services by 55.6 % are using invited tender with pre-qualification as selection criterion by in total 88.9 % of the described cases, which is nearly the same percentage distribution in Fig. 2 by 86.5 %.

3.2 Assignment Criteria

Looking at the most used assignment criterion regardless of project type, it is found to be most economically advantageous offer in 54 (73.0 %) of the 74 cases, see Fig. 3.

The advantage of using most economically advantageous offer is that owner and project manager before the tender process start can specify some planned percentage parameters such as architecture, functionality and price to find the best counselling offer from the incoming offers.

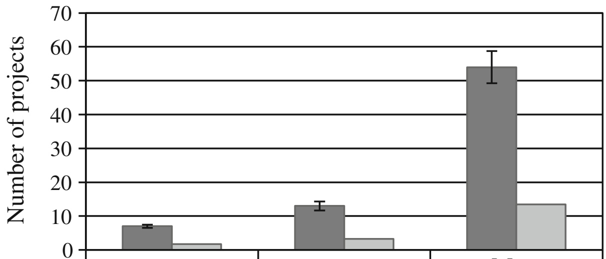
Most economically advantageous offer has therefore the strength of giving the opportunity to find the best offer according to the planned weighting where the weighting of price is reduced by focusing on, for example, softer parameters such as architecture and functionality.

Lowest price is found to be the second most used assignment criterion in 13 (17.6 %) of the 74 cases and has the advantages of using the marked forces to secure the total lowest price, but as earlier described in selection criteria the use of market forces can give later project complication. This is why the combination open procedure tender and lowest price should be carefully considered because the chance that a counsellor will not have the right competencies and resources to manage the construction project safely through increases.

To test if there is a significant use of some assignment criteria and the different construction counselling project types are the null hypothesis tested using a Fisher's exact test, where the null hypothesis was rejected by $0.028 \neq 0.05$.

The rejecting demonstrates a significant use of most economically advantageous offer between the two project types, which is also percentages confirmed by looking at Table 2, where the two project segments restoration and maintenance project by 21.4 % and new construction project by 42.9 % are using most economically advantageous offer that could indicate a significant use of that particular assignment criterion.

The authors are not familiar with the exact reason for the significant use of most economically advantageous offer as assignment criterion in construction counselling services, but one theory could be that using most economically advantageous offer the owner and project manager secure that public construction projects are both evaluated on price and also on a well-planned parameters such as architecture and its compliance of other softer user demands, which can be complicated to evaluate by the criterion lowest price.



	No published data	Lowest price	Most economically advantageous offer
Number of project	7	13	54
Yearly arithmetic mean between 2010 - 2013	1.8	3.3	13.5

Fig. 3 Assignment criteria for all 74 cases with standard error

Table 2 Fisher's exact test for most economically advantageous offer and lowest price compared to project types, 0.05 significance level

Null hypothesis $H_O : \mu 1 = \mu 2$: *Most economically advantageous offer and lowest price are used equally between restoration and new construction projects?*

	Most economically advantageous offer	Lowest price	Total row
Restoration and maintenance projects	3 (21.4 %)	5 (35.7 %)	8
New construction projects	6 (42.9 %)	0 (0.0 %)	6
Total column	9	5	$n = 14$

Fisher's exact test results	
Hyper geometric probability	$H_O : \mu 1 \neq \mu 2$: 0.6667
Two-sided p value	0.0310
Probability $a \leq 0$	0.0280
Probability $a \geq 0$	1.0000

3.3 Selection and Assignment Criteria

Looking at Table 3, the most used selection and assignment combination invited tender with pre-qualification and most economically advantageous offer used in 57.1 % of the involved tender cases regardless of project counselling types. This is further supported by looking at the specific selection and assignment criterion for the two project counselling types at Table 1 and Table 2 as earlier described in the result section of the article.

Table 3 Fisher's exact test for most economically advantageous offer and lowest price compared to open and invited tenders, 0.05 significance level

Null hypothesis $H_O : \mu 1 = \mu 2$: *Most economically advantageous offer and lowest price are equally used between open procedure tender and invited tender process?*

	Most economically advantageous offer	Lowest price	Total row
Open procedure tender	1 (7.1 %)	0 (0.0 %)	1
Invited tender, pre-qualification process	8 (57.1 %)	5 (35.7 %)	13
Total column	9	5	$n = 14$

Fisher's exact test results	
Hyper geometric probability	$H_O : \mu 1 = \mu 2 : 0.6429$
Two-sided p value	1.0000
Probability $a \leq 0$	1.0000
Probability $a \geq 0$	0.6429

The second most used tendering combination is found to be most economically advantageous offer with lowest price as assignment criterion in 35.7 % of the cases, which when looking at the two most used tendering combinations, both use the same selection criterion invited tender with pre-qualification in 92.8 % of the cases.

Finally, the third most used selection and assignment combination according to Table 3 found to be open procedure tender and lowest price in 7.1 % of the cases. The reason for low use of the third tendering combination is not known by authors, but as earlier explained, there is some risks by choosing that combination.

To test if there was a significant use of the selection criterion for open procedure tender and invited tender with a pre-qualification compared to the assignment criterion most economically advantageous offer and lowest price the null hypothesis was tested by a Fisher's exact test, which confirmed the null hypothesis and therefore demonstrated no significant use between the different selection and assignment criteria, see Table 3.

4 Conclusion

The purpose of this paper was to study which selection and assignment criteria were most used in public construction counselling services put out in European tendering, how different types of construction counselling types are using selection and assignment criteria and finally if there was any significant use of some selection and assignment combinations in Danish public construction counselling services.

During the data obtaining, 74 tender cases were identified and used in the processing stage where it was found that invited tender with a pre-qualification process in 64 (86.5 %) of the 74 cases was the most used selection criterion regardless of project type.

Hereafter, a Fisher's exact test was conducted between counselling project type and the two selection criteria used, where the null hypothesis was confirmed by $0.6667 = 0.05$ and therefore demonstrating no significant use of invited tender with pre-qualification process. But by looking at 33.3 % of the restoration and maintenance projects and 55.6 % of new construction project tender cases that use invited tender with a pre-qualification process as selection criterion could there be a tentative indication of a significant use of invited tender with a pre-qualification that was not possible to confirm by a Fisher's exact test based on incomplete data from most of the tender cases.

Looking at the most used assignment criterion regardless of project type, it was found to be most economically advantageous offer in 54 (73.0 %) of the 74 cases, where a following Fisher's exact test rejected the null hypothesis by $0.028 \neq 0.05$, which demonstrates a significant use of most economically advantageous offer between the two project types. Thus is also percentages confirmed by the project segments restoration and maintenance project by 21.4 % and new construction project by 42.9 % use most economically advantageous offer.

To test if there is a significant use of some selection and assignment combination regardless of counselling project type, the tender cases' selection and assignment criteria were tested using a Fisher's exact test where the null hypothesis was confirmed by $0.6429 = 0.05$, and therefore not demonstrating a significant use of one tendering combination, but by looking at the percentages distribution, the most used tendering in 57.1 % of the cases was invited tender with a qualification process as selection criterion and most economically advantageous offer as assignment used in Danish public construction counselling projects.

Further research within the field of European construction counselling selection and assignment criteria could be conducted by including all Europeans countries' public construction agencies to study if the results in such a study are different from other Europeans countries' selection and assignment criteria in public counselling services.

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Delays in the Apparel Manufacturing Industry's Implementation of Mass Customization

Jocelyn Bellemare, Serge Carrier and Pierre Baptiste

Abstract Past research has demonstrated the importance of understanding the mass customization of clothing within the context of trade globalization, which has led to ever more ferocious competition in the apparel industry. But, why is the apparel manufacturing industry so late in understanding this? This paper outlines and discusses the possible causes of the delays of mass customization in the apparel and fashion industry. The study first identifies (based on a number of interviews with apparel producers) the performance indicators and the integration of technologies necessary for the implementation of a system of mass customization in the clothing industry. The interviews with these producers reveal certain factors and characteristics that can explain this delay. The principal cause is the lack of integration between technologies currently in place and those offered by suppliers that do not adequately respond to the needs of manufacturers and distributers.

Keywords Mass customization · Apparel · Performance indicators

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1 Introduction

Although the role of clothing manufacturing has changed greatly over the past few decades, the fashion and apparel industry still remain an important source of economic activity and employment. Following sustained growth in the 1990s, the industry is currently experiencing disruptions as a result of massive imports and economic fluctuations due to e-commerce in its primary markets. Significant breakthroughs by foreign-based newcomers to the industry have only added to existing local competition. Moreover, as apparel products now seem to have an ever-shorter life cycle, a phenomenon exacerbated by the introduction and implementation of new business models, commercial strategies are facing mounting pressure. This situation has forced all manufacturers to revise their organizational strategies in order to survive in this highly competitive market.

In addition to this, apparel companies are busy adapting to all the technological and managerial developments that have taken place in the last few years. Customers' expectations in terms of quality, cost, lead time, and service are constantly on the rise, whereas profits margins have steadily decreased over the past 20 years. To compete, businesses must find new approaches to product development and marketing, such as reducing life cycle times, improving productivity, and redefining customer service. Hence, they have turned to technology to identify potential new approaches to support their business strategies. Technology firms smell the kill and multiply their promises on $\ll$ sure bet $\gg$ new products. Yet, reality often is more down-to-earth; and businesses encounter a number of obstacles on their road to reinvention.

Our research looks into the factors and industry characteristics in large part explaining the apparel industry's difficulties and lateness in implementing one of the most important recent innovations: the mass customization of clothing products. We argue that one of the major difficulties arises from the lack of integration between the technologies presently used by the industry and those offered by the providers of new systems. The products offered do not meet the apparel manufacturers' and distributors' needs and expectations. Our interviews with different stakeholders point to: (1) a lack of technological fluency on the part of both managers and labour, (2) a strong resistance to change in a very traditional industry that still relies on outdated work habits, (3) a lack of proactivity and implementation of strategic or technical watches, (4) minimal investment due in part to the difficulties in borrowing money, and (5) the bad press often given to technology and mass customization implementations by certain important industry actors.

These findings should encourage the actors that make up this industry to re-adjust. The above list of difficulties should also trigger a wake-up call to the new reality in the clothing industry: more demanding consumers, globalized markets, new technologies, etc. Apparel industry businesses must be proactive, adopt, and adapt to new mind-sets and management tools to take full advantage of information technologies. To successfully implement mass customization, it is of the utmost importance that they emphasize analysis, decision making, performance evaluation, and added value. Indeed, flexibility is a must as the market increasingly expects it.

2 Literature

Reviewing the writings on this subject tells us that paradoxically, at a time where the global key word in most industries is standardization, the focus in the apparel industry is on "uniqueness." Fashion is first and foremost a subjective world; consumers are ever more focused on their own needs and expectations and are therefore resisting product standardization [22]. Hence, Piller [12] has identified mass customization as an important development axis. Ashdown [2] confirms that consumer demand for mass-customized apparel is steadily growing and that the capacity to fulfil this demand is made possible by new technologies and information systems. Inala [7] states that mass customization is a highly competitive strategy for organizations offering personalized products. The more the product can be adapted to individuals' requirements, the more competitive the seller can be [8]. Yet, this requires a thorough understanding of consumers' needs and wants.

Currently, some confusion still exists between personalization and mass customization [4]. When garments were tailor-made, each individual piece was cut and sewn for the eventual user; the garment was fitted for a particular consumer [23]. As Pine [14] states this was a hand-made and personalized production. Yet to implement a mass customization program [24], one needs high-volume manufacturing operations based on flexible processes enabling the producer to quickly meet individual customers' demands. As Pine [14] states the success of mass customization is based on a complete integration of the value chain, which must simultaneously perform on two opposing axes: (1) quick turnaround times for (2) products meeting individual clients' specifications.

Tian et al. [18] confirm that consumers increasingly want a personal touch with their garments to make them "unique." Piller [13], they want to exhibit creativity in all domains, particularly with furniture, automobiles, sports accessories, and clothing. This is why, according to Pine [14], in such large markets, business must incorporate mass customization in every step of the process, from a garment's conception to every aspect of its manufacture. But Agrawal et al. [1] see product adaptation to individual consumers' needs as mass customization's main problem, while Von Hippel [21] goes so far as to say that consumers' lack of experience and knowledge make them unable to know exactly what they really want or need. One must therefore simplify and guide this demand. The information technologies used must transform the masses of data into meaningful and understandable information [2]. The objective is clearly to produce realistic garments, yet, the constraints make a compromise between performance, realism, and technical characteristics very difficult. Some suggest that a product configurator may offer the solution.

3 Technological Solution

Many apparel businesses are currently researching technological ways to produce, adjust, sell, and deliver, in a systematic and automatized fashion, personalized and made-to measure products. Brown and Bessant [3] highlight that product configurators, by determining the level of personalization offered, will play an important role in supporting the mass customization paradigm. For Piller [12], the first objective of the configurator is to facilitate the consumer's experience when confronted with a Web site. The configurator is the bridge between the producer and the consumer [7]. Over and above the product decision facilitating function, the configurator should also lead to cost reductions [13] as it allows for time savings when pacing and receiving orders.

A product configurator must be based on a strong technological platform in order to enable a consumer/producer product co-design and co-production. It operates as the interface between consumer and producer and must facilitate this co-creation offering both parties a value-added proposition. At the present time, the configuration of a product that meets the client's requirements is a complex task requiring increased time and effort as the number of product options and components increases. Kincade et al. [8] explain that, as the number of product variations increases, the number of potential errors multiplies, production start-up and lead times extend, and therefore, the number and cost of potential errors can skyrocket. This same observation led Ashdown [2] to highlight the number of challenges one has to currently face to produce a mass-customized garment. Rogoll and Piller [16], for their part, point to the fact that a configurator must fluently interface between different programming languages (different languages are often used in programming for data acquisition from the consumer on the internet, for pattern-making, laser cutting, etc.), yet they must also be fully autonomous. All these human, technological, and product dimensions obviously make the development of an apparel configurator all the more difficult (Fig. 1).

Yet, development is only one part of the challenge: the apparel business must then implement it at both the consumer input end and in production processes. Henderson and Venkatraman [6] point to the fact that performance indicators become all the more important as they offer managers the tools to evaluate whether objectives are met (both short- and long-term). Rogers [15] adds some precision to this point in identifying two types of indicators necessary to evaluate implementation: performance indicators and integration indicators.

One must remember that an apparel producer may perform well, yet be deficient in terms of integration of its technologies (i.e. using highly effective and efficient processes and offering a well-adapted product, yet arriving at this result due to the quality of a company's personnel, resources, and historical management approaches). Performance indicators (stock rotation, return percentage, number of complaints, etc.) enable organizations to know if they are meeting their goals and objectives. They provide information on the efficiency and effectiveness of the use of resources, whereas integration indicators provide a reading of the adjustment in

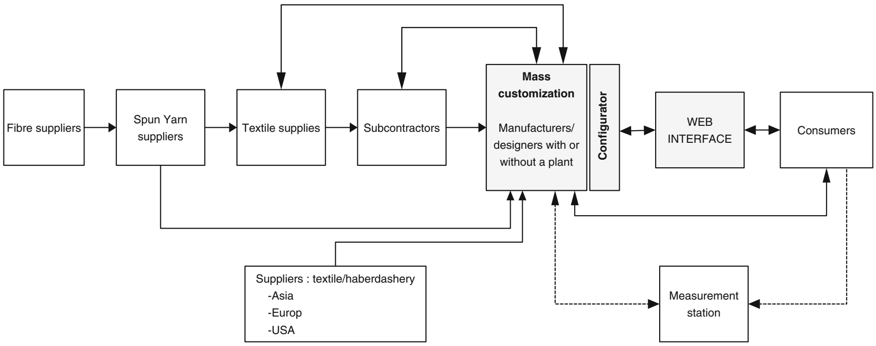

Fig. 1 Configurator in an apparel mass customization context

the technologies used to attain the organization's goals and objectives. They help technology suppliers in fine-tuning their offers to the needs of the apparel producer.

Venkatraman [20] tells us that when business processes and technologies are well adjusted, managers and employees develop a better attitude towards new technologies and a greater openness to mass customization [13]. Thus, our research focuses on the link between business processes (order management, production, distribution, etc.) and technologies currently in use or intended to be implemented. We purport that this will enable us to better comprehend the slowness of apparel producers in adopting technologies to facilitate mass customization.

4 Methodology

Having observed that, despite numerous opportunities, apparel manufacturers have been rather reluctant to adopt mass customization, our research aims at better understanding the apparel producers' use of the most up-to-date technologies in their overall business and decision-making processes. The basic selection criterion for such producers to participate in the research was an expression of interest in developing a mass customization project within the next 10 years. Hence, they must plan on coupling mass customization technologies to their current processes and technologies. The research comprises 20 producers. The interviews and questionnaires used focus on understanding their current systems/technologies integration and the variations found in this aspect within the industry. The questionnaires were handed out on a one-to-one basis and/or sent via e-mail. We also conducted lengthy interviews with three technology suppliers in order to understand their perspectives in terms of technology products/services currently available on the market.

5 Conceptual Framework

The primary objectives of the survey focuses on the integration of new technologies within the operations of clothing manufacturers who wish to implement mass customization. More than just simply recognizing the concept, this will allow us to evaluate whether the available performance and technology integration indicators, touted by the equipment and software companies and presented as important management and development tools, have any effect on the business processes used in manufacturing, distribution, and general management. This will help us understand the elements leading to delays in implementing mass customization in the apparel industry from a technological point of view.

Thus, we asked three specific questions in our study. First, we wanted to know if the level of current results highlighted by the performance and integration indicators (on a scale from high to low) had an impact on the management's attitude towards technology and innovation as well as its intention to pursue mass customization. Second, we wondered whether the results on the indicators employed (performance and integration) had an effect on the business processes. Third, we wanted to know what effects the management, manufacturing and distribution processes in place had on the management's attitude towards technology, innovation, and intention to pursue mass customization.

Figure 2 presents the technology's performance and integration indicators that we position as our independent variables in the model. These indicators focus on the most important areas of improvement put forward by technology and services suppliers to the apparel industry.

Our three dependant variables consist in three types of reactions frequently found in operations management regarding the effects of technology, namely: attitudes towards technology [19], attitudes towards innovation [10, 11, 15, 20], and the actual intention to utilize mass customization [5, 9, 14, 17].

The integration of the existing business processes' impact, on attitudes and intention, to predict and explain the impacts of the indicators stems from to the findings of Henderson and Venkatraman [6] who state that it is through these business processes that the manufacturer is able to form a concrete idea of the level of integration and performance of a particular technology, whether already implemented or yet to be implemented.

6 Results of the Indicators

The first element of our research deals with the producers' current use of technology, as well as the performance indicators used. Our results show that the performance indicators perceived as the most significant are those that focus on data transfer technologies such as EDI, RFID, and bar codes.

Our respondents indicate that technologies that better enable sourcing, production, and distribution operations management will have an immediate impact

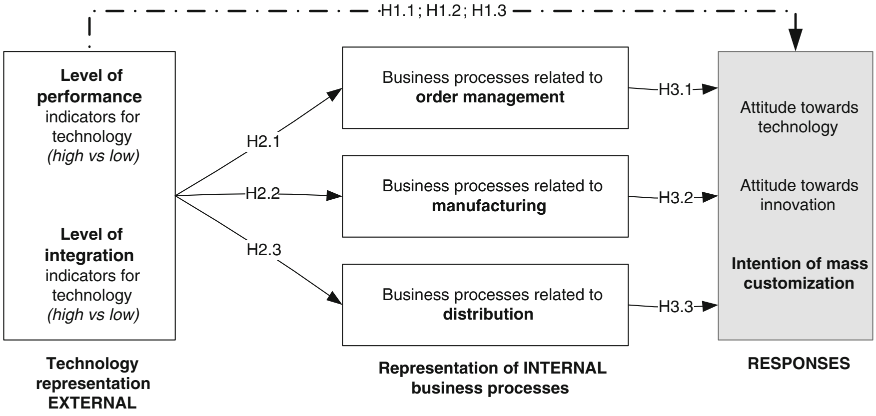

Fig. 2 Conceptual research framework

on business processes, and that both upstream (suppliers) and downstream (distributors, retailers) business partners require their use.

Yet, our research results also show that the critical integration indicators focus on other technologies such as ERP, SCM, EMS, all of which emphasize the optimization of internal processes. Our respondents confirm that implementing and using such technologies would require major changes within an organization's management systems. Some also stated that this implementation often takes quite a bit of time, yet does not bring the expected results.

Our results show that 61 % of organizations use relatively non-integrated technological systems and that their performance indicators are inadequate. Moreover, 12 % confirm that their existing technological systems are "heavy" and hard to manage, and that they present a poor fit with the structure in place in terms of performance and process integration.

Table 1 shows the results of the performance and integration indicator levels for the 20 manufacturers surveyed, on a scale of 1–10 (10 being the highest relative impact).

Figure 3 presents the manufacturers' evaluations of both performance and integration indicators used in operations management on the impacts of technology with respect to our three dependant variables: attitude towards technology, attitude towards innovation, and intention to implement mass customization.

Another notable feature is the lack of innovation, which is not merely a question of technology, according to the suppliers, but is also (and primarily) based on efficient work habits cultivated by motivated and experienced teams—a distinctive set of traits possessed by the workforce of any successful organization. Thus, it appears that the lack of information sharing and best practices within the apparel industry is a crucial problem. We have witnessed that decisions are often made at the last minute and that crisis management is a permanent condition. Indeed, many companies have serious problems with management, control, and responsiveness due to an obvious lack of vision within organizations, both internally and externally.

Table 1 Average indicator levels based on the variable response

Variable response	Level of the performance indicators	Level of the integration indicators
Attitude towards technology	4.613	3.331
Attitude towards innovation	2.472	2.903
Intention to implementation mass customization	6.679	4.254

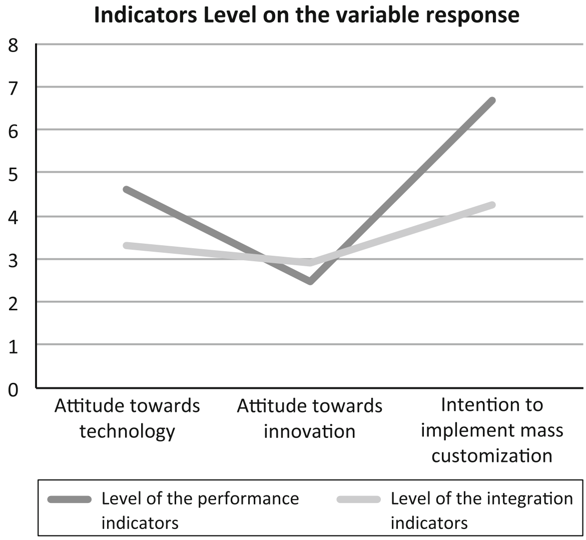

Fig. 3 Indicators level based on the variable response

Only two out of 20 respondents said they were satisfied with the systems in place and are ready to continue to implement mass customization. Technology suppliers also stated that organizations need to better understand that technology is not an end in itself but requires massive financial and personnel investments.

7 What is Mass Customization?

The concept of mass customization as a principle of widespread personalization via the internet seriously puts into question traditional manufacturing techniques and production methods. We asked the following question in our survey: "According to you, what is the minimum number of units necessary for customization to become 'mass customization'?" The responses vary widely according to the experience of the manufacturers. According to them, on average they must have the capacity to produce at least 200 units that respect the customers' quality requirements for it to constitute mass customization. The following table presents the results of this question in our survey (Fig. 4).

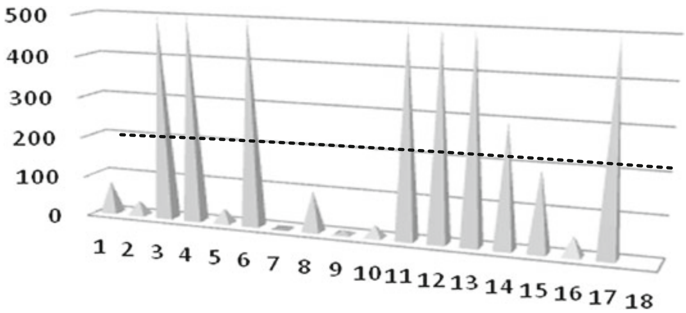

Fig. 4 Production volume necessary for mass customization

Below 200, we can say that we are in the territory of artisanal or "craft" production. It thus follows that several companies currently offering mass-customized products on the web do not have this capability within their business model, which renders them particularly vulnerable in terms of profitability.

8 Perspectives and Limits

Our research validates the idea that the use of performance and integration indicators has a direct and significant impact on the implementation of a mass customization strategy. It also highlights that this observation is in great part due to a fundamental cultural problem. The industry is comprised of a large number of family businesses, managed in a more or less autocratic manner not very conducive to market adaptation and the implementation of revolutionary technologies. Indeed, for these companies, technological innovation is seldom a priority. The generally limited education level of the apparel producers' managers leads to a lack of competencies, of market knowledge, and ultimately of leadership.

Our research shows that apparel producers seldom have a strategic plan and that even fewer invest in a strategic watch, and the information systems in place are often deficient and poorly integrated with the rest of the firm's activities. One cannot help but notice a strong reluctance to change, along with a lack of vision on the part of higher management.

We also have to underline that our research has a number of limits which, viewed more positively, constitute avenues for future research. First, we decided not to consider certain characteristics and traits among producers' and/or managers' that may have an impact on technology adoption (e.g. size of the organization, other market strategies, etc.). Second, our research examined only one subset of one specific sector, which undoubtedly had an impact on its external validity.

9 Conclusion

This study confirmed that performance and integration indicators had a significant effect on the implementation of mass customization, as seen in the responses to our survey questions. They have also helped us understand the factors and characteristics that lead to significant delays in the fashion and apparel industry regarding the adoption of such systems from a technological, organizational, and strategic point of view. Our interviews have confirmed that for the concept of "mass customization" to operate, there must be significant investments made in information decoding and data mining, as well as in all aspects of understanding client relations, as consumers have increasingly less time to spend shopping and at the same time have more demands and needs.

We remain surprised that the results of our interviews and surveys indicate a strong resistance to the introduction of mass customization among manufacturers who want to put in place an element of personalization. However, these results also give us the opportunity to provide valuable information to develop a mass customization program for the garment industry. An analysis of the results allows us to identify five major components that will potentially be useful for such a program: the fostering of a culture of innovation, improved organization, vision, implementation, as well as configuration and design.

Mass customization offers a number of innovation possibilities and may constitute a major opportunity for some apparel industry players. To take advantage of this opportunity, the order givers will have to better understand what is possible in terms of product personalization and on-demand garment production. They will need to radically rethink their marketing and production strategies, remembering always that mass customization must start with consumers, involving them in both product design and production.

Nor should mass customization be considered strictly as a short-term marketing strategy. It may lead to significant cost savings for the producer and greater supply chain integration. It may also provide producers with a better understanding of their consumers, their preferences and wider opportunities for market segmentation. Taking the mass customization route is an avenue to create new opportunities, to give a competitive advantage and a better position to an organization within the global market.

It may be true that the western apparel industry cannot currently compete with producers from "emerging" countries in terms of costs, but a technology-based strategy may yet offer definite advantages.

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Describing Product Variety Using Set Theory

Thomas D. Brunoe, Kjeld Nielsen, Kaj A. Joergensen and Stig B. Taps

Abstract Three capabilities: solution space development, robust process design, and choice navigation are critical for mass customizers. In order to become and stay competitive, it is proposed to establish assessment methods for these capabilities. This paper investigates the usage of set theory as a means for developing metrics and assessment systems. It is concluded that set theory cannot be used as an assessment method directly but is useful in the development of metrics.

Keywords Set theory · Venn diagrams · Mass customization · Capability · Assessment

1 Introduction

In any company, it is essential to offer products that match the needs and desires of customers to achieve sales and profit. This is true for mass producers as well as mass customizers; however, in mass customization, this issue is somewhat more complex than mass production due to a much higher variety and a more complex product structure. As pointed out by Salvador et al. [4]., mass customizers need three fundamental capabilities to be successful: (1) solution space development—identifying the attributes along which customer needs diverge, (2) robust process design—reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs and (3) choice navigation—supporting customers in identifying their own solutions while minimizing complexity and the burden of choice [2, 4].

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In order for companies to be able to establish themselves as mass customizers or for existing mass customizers to improve performance, it is proposed that a set of metrics for assessing the three capabilities is developed. However, in order to formulate these metrics, it should be possible to define the ideal scenario for mass customization. An essential concept in mass customization is product variety. Variety is what differentiates mass customization from other business strategies; however, the variety offered to the customer, the solution space, must be carefully designed, since a too high variety will imply higher costs and a too low variety will imply lost sales, since customers will not be able to buy the product matching their individual requirements [3]. In order to describe the product variety and to describe the ideal situation for mass customizers, in this paper, we describe product variety using set theory. The research question for this paper is thus:

How can sets be used to describe product variety supporting assessment of the three MC capabilities?

In the following sections, the different sets that can be used to describe variety in a mass customization company are defined, and following this, the intersections of the different sets are analyzed to identify the ideal scenario and identify which scenarios may be suboptimal.

2 Representing Variety as Sets

In this paper, we use set theory to represent product variety. When describing variety as a set, it should be defined what an element in the set corresponds to. One possibility would be that each element in the sets will correspond to a unique product variant. Following this, each possible combination of configuration choices would correspond to a variant and thus an element in the set. However, for most mass customization product families, the number of elements becomes astronomical due to numerous configuration variables each with a number of outcomes. For example, when configuring a Mini Cooper online, the configuration choices presented to the customer will result in a number of possible variants well above a 20 digit figure. This is obviously significantly more than the potential market of the Mini Cooper. Assuming that the sale of Mini Coopers is a good representation of the demanded variety, and the Mini Cooper has sold a few million cars and assuming that each sold Mini Cooper is unique, the customer demanded variety will still only be a tiny fraction of the offered variety. Furthermore, we would expect that assessing whether single variants would counter a demand from a customer is simply not possible if the number of variants is high. Thus, it would seem that variants defined as all possible combinations of configuration variables is not an appropriate way to define product variety.

A more simple and comprehensible way of representing the sets may be defining the elements of the sets as the “dimensions of customization.” If a product has a number of customizable attributes and each attribute has a finite

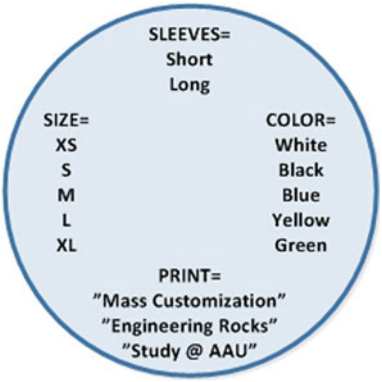


Fig. 1 Illustration of an example of variety

number of values that can be chosen, each value will correspond to a product property, which can potentially be demanded by a customer.

Figure 1 illustrates a set describing the variety, using a fictive example of a customizable shirt with four customizable attributes, from where five different colors, five different sizes, two different sleeve lengths, and three different prints can be chosen. Each element in the set corresponds to one value of a customizable attribute, e.g., the attribute “Color” having the value “Blue.”

If the elements in the set had been each combination of the different outcomes of all variables, the set would have 150 elements, making it less comprehensible than what is illustrated in the figure. While 150 elements may not seem like much, the complexity increases exponentially as more configuration choices are introduced, as with the Mini Cooper for example presented above.

3 Solution Space

Salvador et al. [4] described the capability “solution space” of a company as the ability to “identify the idiosyncratic needs of its customers” and defining the “solution space” that “clearly delineates what it will offer and what it will not.” Hence, the solution space can be interpreted as the initial decision of the company regarding what variety should be offered to the customer. However, a number of processes must be undertaken, from deciding what to offer, until a product is sold to an end customer each representing the solution space. Within each of these processes, changes to the solution space may occur. We assume that most mass customizers will follow the processes illustrated in Fig. 2 or a similar variation in these processes [1].

The variety of planning process is similar to general product planning, and in this phase, the company identifies customer needs and decides on what to offer the customer. The output of this process we define as “initially defined variety.” In the following process, the actual product design and development take place and

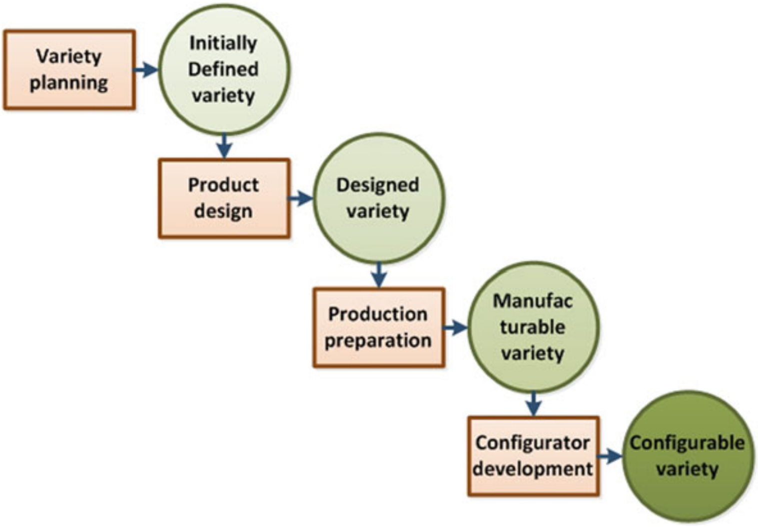


Fig. 2 Diagram of processes involved from variety planning to defined set of configurable variety

the "initially defined variety" is basically a requirement specification for this process. Ideally, the output of this process should be a product family design that perfectly reflects the "initially defined variety," however, for various reasons, the product design may differ from this by either offering more options to choose from or fewer options, which could be due to cost or time constraints in the development project. The output of this process is defined as "designed variety."

Once the product design process is finished, production preparation must take place to ensure that all variants can be manufactured and tools and materials are in place prior to production ramp-up. Again, ideally the output of this process should reflect both "initially defined variety" and "designed variety," however, this may also differ. We define the output of this process as the set "manufacturable variety." This set may be smaller than the previous sets, in case the manufacturing capabilities are not sufficient to produce the designed variety, however, the set may also be larger if the manufacturing system offers greater flexibility than required.

Finally, before a product family can be offered to the customers, the company must typically develop a product configurator, the tool in which customers select and configure the product matching their requirements. The set of products that is possible to configure in the finished configurator offered to the customers is defined as "configurable variety." The "configurable variety" set should correspond to the "designed variety" adjusted for variety that cannot be manufactured and is thus not present in the "manufacturable variety" set. However, if the specification of the variety has errors or if the programming of the configurator has errors, this will not be the case.

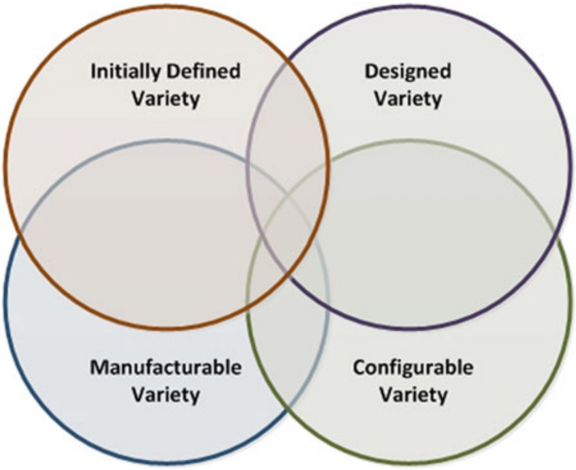


Fig. 3 Illustration of the four sets as output of the development process

As illustrated in the Fig. 3, the four sets defined will intersect each other. Ideally, the four sets are completely convergent; however, as described above due to different reasons, this may not always be the case. In most cases, the "initially described variety," "designed variety," and "configurable variety" will be almost convergent, but these sets will be subsets of the manufacturable variety, since manufacturing capabilities will usually be more flexible than actually demanded as they may be used to manufacture other products than the products in question here.

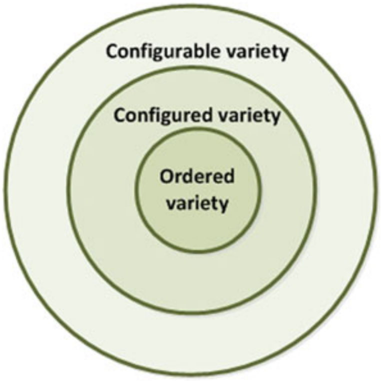
What can be concluded on the above is that the term "solution space" may be interpreted in a number of different ways. All the sets defined above represent the solution space; however, at different points in time. Ideally, the four sets should contain the same variety; however, due to the reasons described above this is not always the case, and when referring to solution space, it is relevant to indicate at what state the solution space is. As the two "states" of solution space "manufacturable variety" and "configurable variety" are the sets that are immediately relevant to end customers, these are the two sets that will be considered in the remainder of this paper.

4 Variety from a Configuration System View

The set "configurable variety" describes which variety is possible to configure, but does not address what variety is actually configured by customers during the sales process. However, if variety is present in the configuration system, but it is never configured, then it brings no value to the customer and is thereby unnecessary.

We therefore, introduce a set, called "configured variety," which contains all variety which until a point in time has been configured. "Configured variety" will by definition be a subset of configurable variety, since it is not possible to configure any variety outside the set "configurable variety."

Fig. 4 Configurable variety set and subsets



However, even if certain variety has been configured by a customer does not imply that this variety is actually sold. Configurations are often made and then abandoned. On the contrary, variety that is sold must first be configured. This leads to the introduction of another set "ordered variety," which again is a subset of the set "configured variety." The relations of the three introduced sets are illustrated in the Venn diagram in Fig. 4.

5 Customer Demanded Variety

Since one of the fundamental capabilities in mass customization "solution space development," concerns identifying the idiosyncratic need of the customers, another perspective of variety is highly relevant—the variety that is actually demanded by customers. For this reason, we introduce the set "customer demanded variety."

Whereas the previously introduced sets are in theory easily identified by a company, since they relate to data created by the company, "customer demanded variety" is less trivial.

Each element of this set would be a current or future demand for a certain product property from any customer. Identifying each element in this set is in reality impossible. This would require identifying each potential customer and having these describe their future demands for a specific product type. Although it is impossible to define each element of the set "customer demanded variety," it is very important to address this set, since the elements in this set is what determines success or failure for a future mass customized product.

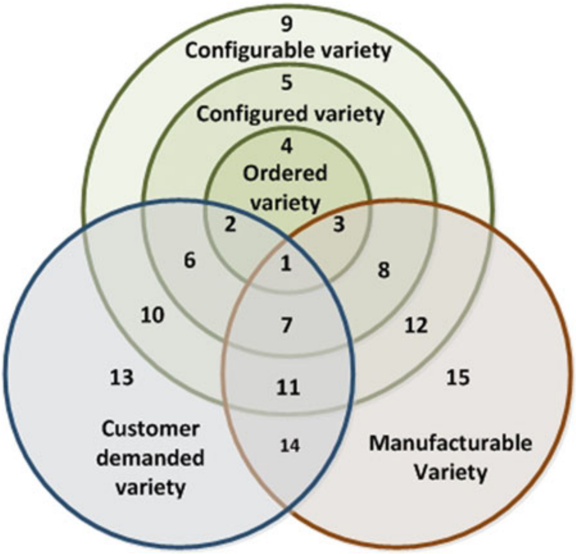


Fig. 5 Intersections of sets defined for mass customization

6 Intersections and Subsets

In order to evaluate to what extent set theory can be used to evaluate mass customization capabilities, the intersections and subsets of the sets introduced earlier are analyzed. The sets are numbered in the Fig. 5 for easier reference in the text in Table 1.

6.1 Relation Between Sets and Capabilities

Since the purpose of this paper is to evaluate whether using set theory can be utilized to evaluate mass customization, all the sets presented above have been analyzed to identify what deficiencies in capabilities may result in elements present in each set. These relations are indicated by an X.

As it can be seen from the Table 2, set one implies no issues in relation to the three fundamental capabilities. However, all other sets indicate some sort of issue that can be attributed to one or more of the capabilities. Furthermore, it can be seen that choice navigation and robust process design may be difficult to distinguish between by observing the sets, since many sets relate to both capabilities.

Table 1 Evaluation of intersections and subsets of mass customization capabilities

Set	Characteristics
1	This intersection is the “sweet spot” of mass customization, since this is where there is a customer demand for a specific option, it is configured and sold and it can be manufactured by the mass customizer. This can be said to be the ideal scenario of mass customization
2	In this intersection, there is a customer demand for a specific option, which is also configured and sold. However, since the option is outside the manufacturable variety, the mass customizer will not be able to actually deliver the product containing this option. This would require the mass customizer to either cancel the order or change the configuration to fit the configurable variety, possibly changing the characteristics of the product compared to what was actually desired by the customer
3	In intersection 3, an option is configured, sold, and manufactured; however, is outside the manufacturable variety. This implies that a customer has purchased a product with undesired characteristics. This may ultimately lead to unsatisfied customers and possibly customers returning products to the manufacturer, since it does not meet expectations
4	Here, an option is sold, for which there is no demand and cannot be manufactured. Since the product cannot be manufactured, the customer will never receive the product, and what happens in this scenario is hence similar to intersection 2
5	In this set, an option is configured, but never ordered. Also it is outside what can be manufactured and outside the customer demand. However, since the customer does not order the product, as the configuration is abandoned, possibly due to the fact that the configuration does not correspond to the demanded variety, no order needs to be canceled
6	Here, a configuration is performed outside the manufacturable variety but within the demanded variety. The configuration is not ordered, although it is within the demanded variety, so the order does not need to be canceled, which would be the case if the configuration was ordered
7	Here, a configuration is performed, which can be manufactured and is in the customer demanded variety. However, the configuration is abandoned and thus not ordered. This could be due to the customer not being able to perform the configuration or get the necessary information about the product, thus canceling the configuration instead, i.e., improved choice navigation could have implied that elements from set 7 moved to set 1 increasing sales
8	Here, a configuration is performed, which is outside the customer demanded variety but within the manufacturable variety and the configuration is not ordered. This could be due to the customer not being able to find the option required. Hence, no matter the performance of choice navigation, this configuration would not lead to a sale
9	This set contains options that can be configured and are outside the demanded variety and cannot be manufactured. Since it cannot be manufactured, it is a result of a faulty implementation of a product configurator, however, it has no consequence as it is never configured
10	This set contains options that can be configured, have a demand, but are outside the manufacturable variety. As with set number 9, this is a result of a faulty implementation and since it is within the customer demanded variety, there is a risk that a customer will configure and order it, but in that case, the company would need to cancel the order as it cannot be manufactured

(continued)

Table 1 (continued)

Set	Characteristics
11	In this set, there is a match between what is demanded, what can be manufactured, and what can be configured. However, since no customers actually configure this option, something is keeping them from choosing from this variety. This could be a result of bad choice navigation performance and would indicate a potential for increased sales, if choice navigation was improved moving elements from set 11 to set 1
12	This set contains variety, which can be manufactured and configured, but is outside the customer demand and is never configured. This is thus unnecessary variety and could be removed from the product portfolio with no consequence
13	Set 13 contains unfulfilled customer demanded variety. This variety cannot be configured and cannot be manufactured. This variety is thus potential new business for mass customizer; however, it may be very difficult to identify
14	In this set, there is a match between the variety, which can be manufactured and the variety that is demanded. However, since it is outside the configurable variety, customers are not able to configure and order the product and this is thus an unfulfilled business potential. There may be a reason for the company not offering this variety in a configurator; however, it is likely that the reason for it not being offered is a faulty configurator implementation
15	Set 15 contains variety that can be manufactured, but is not demanded and not possible to configure. This is thus a result of developing products and manufacturing capabilities that is not utilized

Table 2 Matrix showing how occurrences of elements in specific sets can indicate deficiencies in the three fundamental mass customization capabilities

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Solution space development			X					X				X	X		X
Choice navigation		X		X	X	X	X		X	X	X			X	
Robust process design		X		X	X	X			X	X					X

7 Discussion and Conclusion

The aim of this paper was to investigate if observing different sets representing product variety in different ways could contribute to assessing the three fundamental mass customization capabilities “solution space development,” “robust process design,” and “choice navigation.” By populating the generic sets with elements of “configuration options,” an element present in a specific subset or intersection would according to Table 1 indicate an issue within one or two of the capabilities. Hence, it can be concluded that using set theory to describe variety can be helpful toward assessing mass customization capabilities. There are, however, a number of issues that need to be considered doing this.

To perform an analysis of the sets in real life, historical data would need to be present, at least to represent what has been configured and what has been ordered. This data would need to be registered over a period of time. Within this time span, certain configuration options may move from one set to another, if e.g., the configurable variety is changed or manufacturing capabilities are changed. Furthermore, using set theory on "configuration options" will not distinguish whether a certain choice has been made once or one million times. If an assessment method is based purely on set theory this would likely be an issue, since including certain variety would appear equally profitable no matter how frequently it is sold. Hence, set theory appears to be useful for developing metrics for assessing mass customization capabilities; however, evaluating solely on the number of elements in certain sets is likely not a viable approach.

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Design and Evaluation of a Reconfigurable Manufacturing System

By the Use of the 2D/3D Computer Simulation

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Abstract In modern manufacturing industry, reconfigurable manufacturing system (RMS) is a promising concept in the research arena. A new RMS system structure has been recently designed by a large consumer goods manufacturer in Europe, aiming to improve its production efficiency. This paper shows an exploratory research on the (re)configuration procedure and evaluation of the RMS philosophy based on the new RMS structure, which is part of the RMS research in University of Southern Denmark. Tecnomatix Plant Simulation is used for system analysis and optimization. Results from simulation show that the RMS implemented in this consumer goods manufacturer can be effectively (re)configured as part of the daily operations, and the configuration is analyzed by computer simulation before release. Flexibility can be increased considerably meanwhile the system can maintain an acceptable productivity.

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Keywords RMS design · Performance evaluation · Modular manufacturing · Plant simulation

1 Introduction

With the progress of globalization, it is well recognized that the manufacturing industry is facing new challenges, include fierce competition, turbulent market demand, more complex product management, highly customized product, etc. [1]. This trend has forced industrial companies to embrace more flexibility, adaptability, and responsiveness on their manufacturing system. Dedicated manufacturing lines (DML) have the advantages with high productivity and low unit cost yet its adaptability is low. To ramp-up a DML dynamically is very expensive and time-consuming. The use of flexible manufacturing system (FMS) shows advantages when producing highly customized products. FMS is often composed of computerized numerical control (CNC) machine units, and the productivity of FMS is not sufficient for mass customization. Under such circumstances, a cost-effective, productive manufacturing system with the ability to rapid change is crucial to the industry [2–4]. Koren and Mehrabi have introduced a concept of reconfigurable manufacturing system (RMS), and six core characteristics of RMS have been summarized as modularity, integrability, customization, scalability, convertibility, and diagnosability. Based on the principles of RMS, a consumer goods manufacturer in Europe (note as CGM in this paper) has designed a new RMS structure (named RMS-L in this paper) to address its own manufacturing problems between productivity and flexibility. The current manufacturing line in CGM is generally a DML. CGM investigated the RMS concept within an industrial perspective and decided to use computer simulation to exam the performance of the concept without having to invest in any hardware [5]. In addition, a research group has been established to simulate and evaluate the reconfigurable assembly system of CGM.

RMS-L is constructed by modular base units with dedicated tools and conveyors installed on top [5]. The structure of one modular base unit is shown in Fig. 1 (left). Up to four conveyers could be installed on the top of the base unit pointing at four directions. The conveyors can transfer materials forward or backward. The centerpiece (round area in the center) is used to deliver elements in the system to a desired direction. The four red bars placed above the conveyers represent the positions for tools to be installed, and only one tool at one position.

The base units could work individually and autonomously or could be easily connected and work cooperatively as a bigger system. Usually, the RMS-L need to be reconfigured according to the requirement of the different production processes. The reconfiguration process could happen on tools level (only change the tools) or on a system level (change the layout of base units). Figure 1 (right) illustrates some possible configurations of RMS-L on the system level. 3D models of the RMS-L have been created using the computer simulation, see Fig. 2. They are

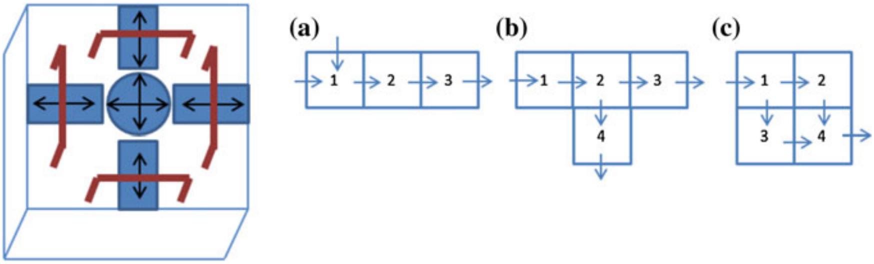

Fig. 1 RMS-L base unit and possible RMS-L configurations

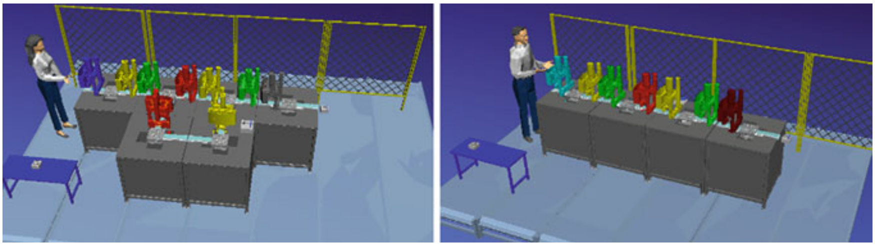

Fig. 2 3D models of RMS-L and tecnomatix plant simulation

built based on corresponding 2D models, which are used for system analysis. 3D simulation shows how the system is actually working, facilitating the discussion between colleagues and system designers. Moreover, it could give suggestions to the factory layout designers on the use of space and other resources. This article attempts to explore the system configuration and to evaluate the performance of the new RMS (RMS-L) in CGM.

2 Method Exploration

Based on the configuration procedure proposed by Koren and Shpitalni [1], a possible configuration procedure for RMS-L is developed in this section. This procedure is applied during operation while producing a single product type (see Fig. 3 shows).

2.1 Calculating Minimum Number of Tools

Based on the tact time constraints, the minimum tools calculation for each process can be preliminarily decided. For further illustration, a practical and simple example is introduced. There are four processes in a manufacturing task (polish,

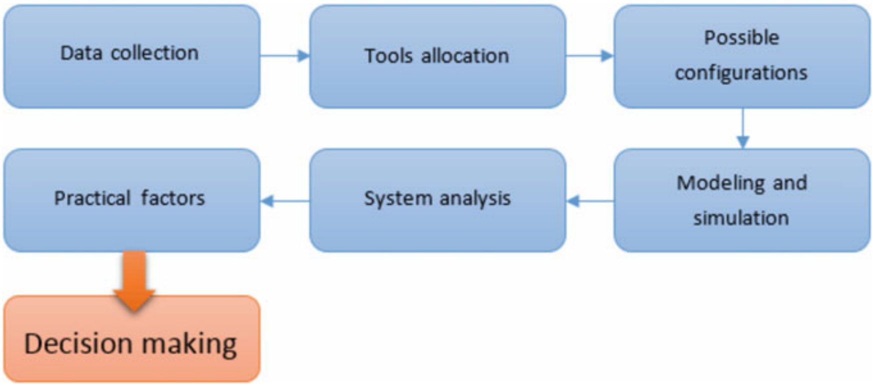

Fig. 3 Procedures for configuration of RMS-L for manufacturing a single product type

Table 1 Tools allocation for different processes

Process	Polishing	Decoration	Assembly	Testing
Processing times	3 s	6 s	1.5 s	3 s
Number of tools	2	3	1	2
Cycle time	1.5 s	2 s	1.5 s	1.5 s

decoration, assembly, and test). Daily demand of the product is e.g., 10,000 pcs, and the system can operate continuously for 8 h per day. The data for the system are mean values, and the real times might vary stochastically to some extent, yet have little influence here to the elaboration of the configuration method.

According to the manufacturing requirement, the tact time is 2.88 s, thus more tools need to be integrated into the system to reduce the cycle time of each process down to 2.88 s. Theoretically, eight tools are needed in the system (see Table 1).

With eight tools, the system can theoretically reach the pulse time of 2 s. In such case, the total daily throughput could be 14,400. However, considering the complexity of the RMS-L structure and the influence of the transit system (conveyers and centerpieces) and the availability of the whole system, the actual configuration might not be able to achieve the exact cycle time for each process. Thus, it is still difficult to decide whether the configuration with eight tools could accomplish the manufacturing task.

2.2 *Analysis of Alternative Configurations*

Figure 4a shows the basic RMS-L configuration, which contains only one tool for each of the four processes. The black arrows indicate the material flow. Due to the flexible structure of the RMS-L, the configuration based on the tools allocation in Table 1 could be various. Figure 4b shows one of the configurations that strictly follow the tools allocation table.

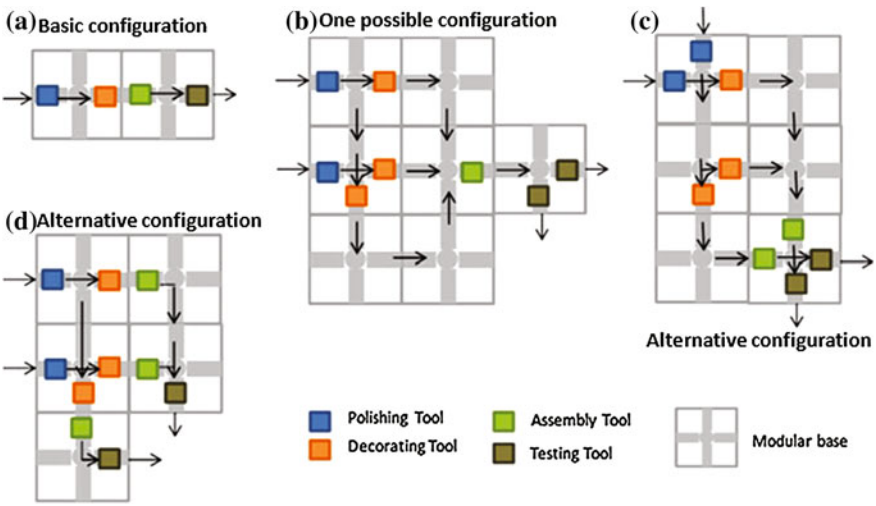

Fig. 4 Possible configurations of RMS-L for consumer goods part processing

This configuration may have the capability for accomplishing the production task, however, redundancy exists in the system since three base units are working only as conveyers without any tools installed. Usually, one base unit might be much more costly than a single tool. Thus, it might be more cost-effective to use as few base units as possible. Based on configuration (b), two other configurations are designed as alternatives, Fig. 4c and d. Configuration (c) has saved one base unit at the expense of one more assembly tool, compared with (b). As for (d), two base units are saved at the expense of two more assembly tools. In a situation where there are no more than five available base units but enough assembly tools, configuration (d) would absolutely be the best choice.

The analysis of the configurations above is based on an ideal environment where transit system (conveyers and centerpiece) can run fast enough and have little influence on the performance of the whole system. However, in real-life manufacturing system, the transit system may have considerable impact on the performance of the whole system, especially when the tools are acting so quickly that time spent on a tool is close or even less than time spent on jointed conveyers. Computer simulation is essential to make sure that the system has the capacity to meet daily demand, especially when the whole system is considerably complicated.

2.3 Computer Simulation and Analysis

Computer simulation gives the opportunity to test alternative solutions and to find the optimal one in a cost-effective way, since the real-life testing can be time-consuming and costly and mathematical ways can be very complicated to involve all factors. Computer simulation result shows that the system pulse time of the four configurations in Fig. 4 are 6.0, 2.7, 2.5 and 2.1 s, respectively. Thus, configuration b, c, and d can all accomplish the production goal since their pulse times are less than the required tact time (2.88 s). However, configuration b actually needs more base units (seven units) with fewer tools (eight tools) than configurations c and d. The availability of the tools or the base units should be considered when deciding which configuration to use. By contrast, configuration d is probably a better choice as it runs faster than other configurations with the least base units (usually base units are more costly than tools). Besides, the difference in pulse times between configuration b, c, and d also reflects the influence of transit system (conveyors and centerpieces), showing that the reduction in extra transportation could increase the productivity considerably in this case.

When the configuration model has been built and capacity has been proved adequate for the production task, it is necessary to know in detail how the system actually works and whether the system or the material flow is actually balanced. A balanced system with properly allocated material flow will contribute to the stability and sustainability of the system (See e.g., [6]). With the help of specific analysis tools in computer simulation, the RMS-L system can be adjusted to its best working state and the performance can be optimized.

2.4 Making the Final Choice

Following the procedures, probably only a few configuration options are left. Accordingly, some practical factors might be considered to make the final choice. Some possible factors could be as follows:

1. The availability of tools or base units
2. The cost to run an extra base unit or an additional tool
3. The cost of making new tools or base units, on both monetary and time aspects
4. The space availability.

The decision maker should consider the weight of each factor specifically in the manufacturing situation, decide which factor would be the most important one for the company, and make the decision accordingly. In the example case, configuration d has a pulse time of 2.1 s, which means its productivity is much higher than that of configuration b and c, showing better adaptability to the environment. Besides, less base units means less operating costs. Thus, configuration d would be the best choice.

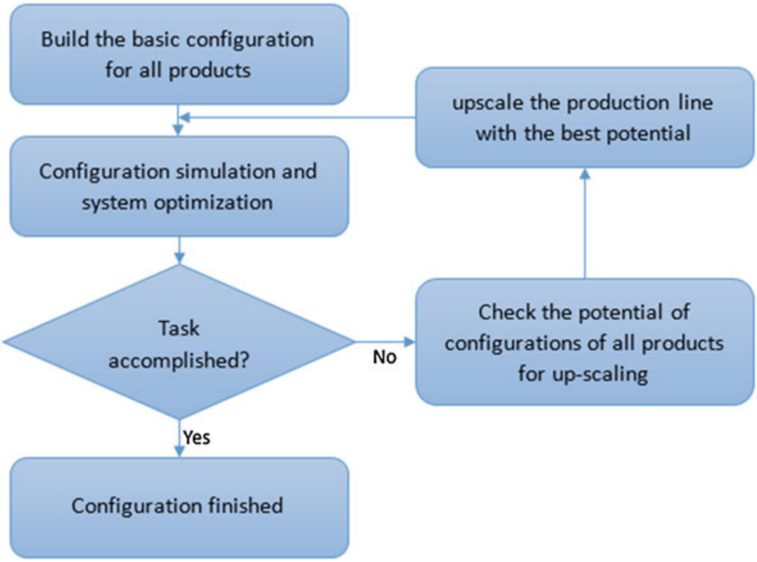

Fig. 5 Procedures to build configurations for multiproduct manufacturing task

2.5 RMS-L (re)Configuration in Multiproduct Manufacturing Task

Procedures above demonstrate how to configure an RMS-L system when the product demand and time limitation are given as constraints for producing one product type. When dealing with more product types, it will be more complicated since each product may probably need one unique configuration. One possible method is to divide the total available time into several slots and assign each one slot to each product. With the number limit and the time limit assigned, the configuration for each product can be built according to the previous procedures. However, the length of timeslot is challenging to define and it can potentially cause waste and unnecessary difficulties. Another possible way is to test the alternative configurations individually, which is actually feasible with the help of computer simulation. The procedures can be depicted in a flow chart (see Fig. 5).

Basic configuration is the configuration with only one processing tool for each process. Starting from the basic configurations, all possible systems would be easily simulated and tested by computer simulation, until the proper ones are found. According to the procedure shown in Fig. 5, the systems are up scaled in an order depending on relative system potentials. When considering the potential of one-specific configuration to be up scaled, several factors can be considered:

1. The complexity of the configuration: the one with simplest configuration has the priority.

2. The relative time consumption of each process: the bigger time difference exists between processes, the more potential the corresponding production system has.
3. The total time consumption for producing some type of product: the one with longest production time based on the basic configurations simulation has the priority.

The three factors are listed in a sequence that is from the one with most significance to the one with the less, according to experiences acquired from the research. However, the sequence could be different in specific situations, and more research is expected in this area in the future.

3 Performance Measurement for RMS

3.1 Measurement Model Design

Based on the performance measurement research (See e.g., [7, 8], this paper designed a simple model to evaluate the productivity and flexibility performance of RMS-L.

1. Productivity measurement

Two metrics about productivity are involved, namely pulse time and productivity rate.

The productivity rate is defined in this paper as:

In the test period,

$$\frac{\text{total output}}{\text{the input cost}} \tag{1}$$

where input cost includes labor cost, raw material cost, overhead cost; and depreciation cost.

2. Flexibility measurement

The measurement of flexibility consists of two different types of flexibility, namely product flexibility and adaptability.

The product flexibility is in the test period,

$$\frac{\text{times of changeover}}{\text{total changeover time}} \tag{2}$$

The adaptability is

$$\frac{\text{total output}}{\sum_{i=1}^{i=P}(\text{output}_i + \text{inventory}_i - \text{demand}_i)} \tag{3}$$

P is the number of days of test period.

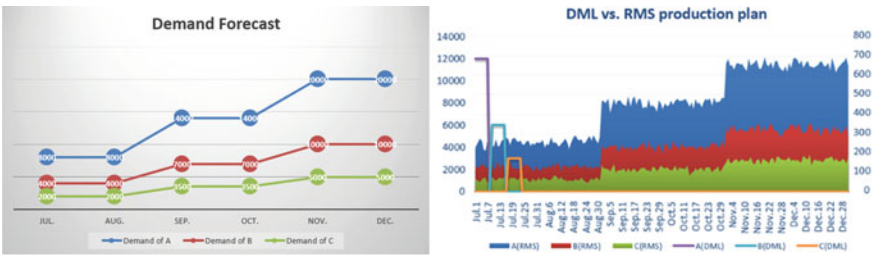

Fig. 6 Demand forecast and production plan in test period

3.2 Test Scenario Design

The evaluation is based on a real case example in CGM, where a products family (three products A, B, and C with similar manufacturing processes) need to assembled and delivered for sale as a pack. Two scenarios are used in the process of performance measurement. Firstly, this paper attempts to investigate and quantify the comparison between RMS-L and DML in CGM. Secondly, this paper intends to explore the potential capacity as well as limitations about RMS-L. Therefore, a more generalized scenario is required.

1. Scenario one

The demand of three products varies on a daily basis and the forecast figure could be drawn based on historical data. The daily demand figure is random numbers generated by MATLAB following Poisson distribution, where the expected value is the demand forecast. In probability theory, Poisson distribution expresses the probability of a group of discrete events occurring in a fixed interval of time. In CGM's case, the custom demand could be regarded as discrete events [9]. Under the same circumstances, the production plan of RMS-L and DML is distinguishable.

Figure 6 shows the demand trends and corresponding production plan. To measure the performance, the total output of the products A, B, and C (the numerator of metrics) is controlled therefore the denominator can be compared. The production plan of current DML is that one product will be produced dedicatedly at first afterward the changeover of system occurs. The second product will be produced for the next period etc. The production period is determined by the demand forecast (e.g., one week in CGM). After all three products are produced, then the DML will be changed to produce other product family. The inventory of product A, B, and C is sufficient for the demand of a long period, such as half a year. On the other hand, for RMS-L, it is anticipated to have the adaptability to follow the turbulent demand. Therefore, the plan in RMS-L is not according to the forecast but to the real demand coming of every day.

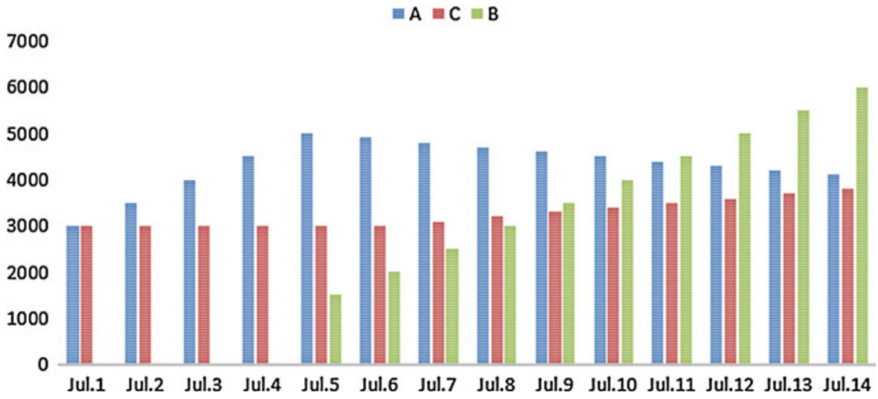

Fig. 7 Assumed product demand for scenario two

	DML	RMS
Pulse time	2.3s	A and C: 2.6s B: 3.1s
Productivity rate	Location 1: 1.043 Location 2: 1.329	Location 1: 0.858 Location 2: 1.083
Product Flexibility	0.002	27.600
Adaptability	0.010	1.160

Fig. 8 Comparison results in scenario one

2. Scenario two

The second scenario is a reasonable expansion of the first scenario since CGM is interested in the potential of RMS-L. The test period is 14 days with 8 h per day. RMS is anticipated to overcome some challenges—rapid scale up, flexible production, and new product arrivals. Figure 7 depicts the assumed product demand of the test, where the demand will force RMS-L to scale up. Besides, a new product in the family, product B will be introduced in the middle of test period.

3.3 Test Results and Analysis

The test results are showed in Fig. 8 based on four metrics. Currently, CGM has two factory locations, and the cost is different hereof the results are separated. Therefore, the results indicate that the productivity performance of RMS-L is app. 80 % of the productivity of DML, from the dimension of speed and efficiency (see the result from pulse time and productivity rate). Besides, the labor time in RMS-L is 16 % higher than the labor time in DML because besides the regular workers, the process of reconfiguration requires engineers. The changeover time of the

configuration	Jul. 1-4	Jul. 5-6	Jul.7-10	Jul.11-12	Jul.13-14
Product A	Basic	Basic	Up scale	Up scale	Up scale
Product B	0	Basic	Basic	Basic	Up scale
Product C	Basic	Basic	Basic	Up scale	Up scale

Fig. 9 Configuration results in scenario two

system in RMS-L is much shorter than the time in DML (see the huge improvement on product flexibility). In the test, RMS-L reconfigured three times per day on average. Therefore, compared with DML, RMS-L can provide great advantages on flexibility (see the result from product flexibility and adaptability). The rapid changeover of the system is the main enabler.

Figure 9 shows the configuration results of RMS-L in scenario two. With the increased demand and product variety, RMS-L is up scaled four times during the test period (happened on July 5, 7, 11, and 13). Therefore, within the product family, RMS-L can process more product varieties with little influence on productivity. In July 5, for example, RMS-L can handle one more product with very little negative effects on its productivity. Moreover, the output scale of RMS-L can be ramped up without too much effort on time and cost. Lastly, Inventory level is reduced in RMS-L (adaptability increased from 0.01 to 1.16). The product batch size is much smaller than in DML, at least one batch (product A, B, C) can be produced during one day in RMS-L.

4 Conclusion

This article shows an exploratory research on the (re)configuration method and performance evaluation for RMS-L, which is part of the RMS research at SDU. The (re)configuration methods are separately designed according to the type of manufacturing task: single product or multiproduct manufacturing task. The (re)configuration process of the RMS-L is managed manually with the help of computer simulation. When the system gets more complicated for higher capacity in the future, the (re)configuration process would more rely on computer analysis for system optimization.

Within the process of exploration and evaluation, Tecnomatix Plant Simulation plays a significant role in the research. On one hand, it helps obtain data of RMS-L by modeling the system and simulating its operation. On the other hand, the computer simulation helps to analyze and further optimize the configuration of RMS-L.

In the testing case, RMS-L has shown great flexibility of production capabilities and outstanding responsiveness to demand changes, compared to the currently used DML system. The modular structure of RMS-L enables frequent and precise changes in layout that fits current needs and demand. Thus, the changeover of the system will not require too much time and money efforts. The inventory level can be greatly reduced and small batch production can be achieved in RMS-L—due to the high system responsiveness, RMS-L is able to produce smaller batches in frequent periods (such as one batch per day in the testing case) and reduce its inventory level and inventory cost accordingly. Besides, labor force working time could increase greatly when manual changeover happens frequently. However, the RMS-L has the potential to integrate new technologies such as robot arms to replace labor force. The performance evaluation of RMS-L application in CGM has demonstrated great adaptability of the RMS-L concept, and its potential to deal with new challenges in the globalized environment.

5 Discussion

In this paper, the RMS-L configuration procedures has been explored and developed, which will contribute to deciding the proper system configuration according to the requests of different production tasks. The procedures are applicable with the use of computer simulation. When the manufacturing processes are relatively simple (such as the cases in this paper), the theoretical calculation (tact time constraint) of the tools is quite applicable and can lead to a proper system configuration with enough capability for production task. When the number of the manufacturing processes becomes bigger or the system has to deal with high volume, the complexity of RMS-L configurations will increase dramatically because of the special structure of the base unit, which has four connective interfaces. In such case, the applicability of the calculation for allocating the tools, which is based on the constraint of tact time, might be weak, as the real configuration may not be able to follow the calculated tools allocation. Therefore, the performance of the RMS configuration can differ a lot from theoretical anticipation hence the procedures of configuring RMS-L will mostly rely on computer simulation analysis.

The RMS-L configuration method does not involve the influence of the transit system (conveyers and centerpieces) on the base unit. Practically, when the processing tools spend much more time than the centerpieces or the related conveyers spend, the transit system will have little influence on the system. However, when the transit system, especially the centerpiece, consumes more or less the same time as the tools, the centerpiece may become the bottleneck. In such situations, computer simulation and analysis will be crucially important to decide the system configuration.

The research has presented practical procedures to design the RMS-L configuration with the right capacity to fulfill the production requests. However, if the production demand changed frequently with huge fluctuation, it would be feasible and much more efficient to create a database on the demand and corresponding configurations in advance using computer simulation. As for multiproduct manufacturing tasks, the database will be much more difficult to create, which can be a subject for future research.

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Design Configurator Requirements for IS Integration

Pasi Paunu and Marko Mäkipää

Abstract Configurators are essential tools in mass customization. While sales configurators and product configurators have received a fair amount of attention, a new type of configurator has emerged for area of order engineering: design configurator. Design configurators can be used to automate order engineering and decrease lead-time for product quotations and customized designs. Thus, they can bring ETO companies closer to mass customization. In the literature, the concept of design configurator has been suggested and this paper examines the requirements of such configurator for IS integration through illustrative case example. By determining the requirements and integration possibilities of design configurator, this study will greatly benefit different industrial contexts when considering a configurator solution.

Keywords Configurator · Engineering to order · Design · Information systems · Integration · Requirements

1 Introduction

Competitive market dynamics push companies to offer ever more variety to customers and even treating them individually by reconfiguring their product or service to meet each customer's needs [1]. At the same time, increased cost competition drives companies to reduce costs directly or by developing new products that deliver what customers need more cheaply [2]. Generally, increasing

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product variety negatively effects cost efficiency, resulting in potentially weaker competitive position. Hence, those companies, which can deliver sufficient variety at competitive cost structure, can achieve an important market advantage over less efficient and less effective competitors [3].

A challenge for most companies craft customizing their products today is to continue delivering quality and high customer value while curtailing costs and shortening delivery time. Mass customization is proposed as a promising approach to compete in this kind of competitive environment [4, 5]. By using flexible processes and organizational structures [4], mass customization enables companies to provide "tremendous variety and individual customization, at prices comparable to standard goods and services" [6].

The center of mass customization is the customer co-design process. Customers are invited to participate in value creation process by defining, configuring, matching, or modifying an individual solution, inside a large but fixed solution space [7]. Configurators support this process by collecting customer needs and matching them to predesigned product features. Traditionally, configuring a product, rather than designing it, has implied that no component design activities are needed to define the required product variants [3]. However, advances in technology, especially in parametric 3D CAD and design automation tools, has contested the definition of design activity excluded in product configuration.

While sales configurators and product configurators have received a fair amount of attention in the literature, this study explores a third type of configurator for use in craft customization: a design configurator [8]. With advanced information technology utilizing modeled engineering knowledge, a design configurator can be used to automate design activities and decrease lead-time for product quotations and customized designs. This brings the potential to respond quickly to customer requirements and generate a range of variant designs to meet specific requirements [9]. Thus, design configurators can bring craft manufacturers closer to mass customization.

Sales configurators are typically used by customers themselves or by professional sales personnel. They offer an easy to use interface to place an order in digital format and to make sure that product specification is completed and error free. When used together with product configurator, sales configurator typically collects the customer requirements and delivers them for product configurator for precise product definition generation. When used as a stand-alone system, sales configurator either locates the best matching product for customer requirements or configures the product from major modules and options. With complex products with high level of offered customization, a product configurator can be used together with sales configurator or as a stand-alone solution for internal sales. It is typically used to combine and verify composition of component and modules to create a validated customized product. Design configurators, on the other hand, are based on parametric configuration of components, modules and whole products, instead of merely modular configuration of predesigned components and modules. It produces individual drawings by manipulating parametric 3D CAD models, yet inside predefined limits, offering greater possibilities for customization. It can be used as a stand-alone solution for internal sales or sales support, or it can be used together with sales and product configurators. If used in combination, sales configurator is used to collect customer requirements and to produce sales documentation, product configurator configures the modular parts of product and the design configurator generates CAD drawings for parametric features of the product.

In the literature, few practical examples can be found [8–10] as well as proof-of-concepts [11] showing first efforts toward complete design configurator. Also, an approach for modeling manufacturing requirements in design automation has been discussed [12]. This paper contributes this stream of research of configurators by describing an example of craft manufactured product and the information systems integration requirements it places for a fully operative design configurator. The research method is mainly conceptual–analytical research method supplemented with an illustrative case study. The study is based on existing literature on configurators, the conceptual definition of a design configurator, illustrative case example and subsequent analysis for information system requirements

The rest of the paper is structured as follows. In Sect. 2, an example product is introduced to illustrate a craft customizable product and its qualities. In Sect. 3, the configuration process for defining the product is presented. In Sect. 4, the requirements for information systems integration to build a design configurator are drawn from the basis of configuration process of an example product. Finally, in Sect. 5, the paper is finished with conclusions, limitations, and future research recommendations.

2 Case Downhill Skis

Downhill skiing, also called as alpine skiing, is a sport in which the skier slides down snow-covered mountains or slopes wearing skis with fixed-heel bindings. Skis used for sliding downhill are a construct of narrow strip of wood, plastic, metal, or combination thereof worn underfoot to glide over the snow. Substantially longer than wide and characteristically employed in pairs, skis are attached to boots with bindings, either with a free, lockable, or permanently secured heel [13].

Modern type of downhill skis have over a hundred years of history behind them originating from Norway circa 1850, but the skis of the old have very little resemblance with the typical downhill skis mass produced today [14, 15]. They come with various shapes and forms and have multitude of options for a customer to choose from. Even though the variety in ski models is quite large, the basic construction attributes in manufacturing are quite simple: the width, length, turn radius (accomplished by sidecut), and the rocker type of the skis. These four basic features of the ski combined with the skier's height, weight, and personal style preference are the starting points for making good downhill skis.

Looking more closely on the construction of skis the baseline design has five major manufacturing layouts [16, 17]:

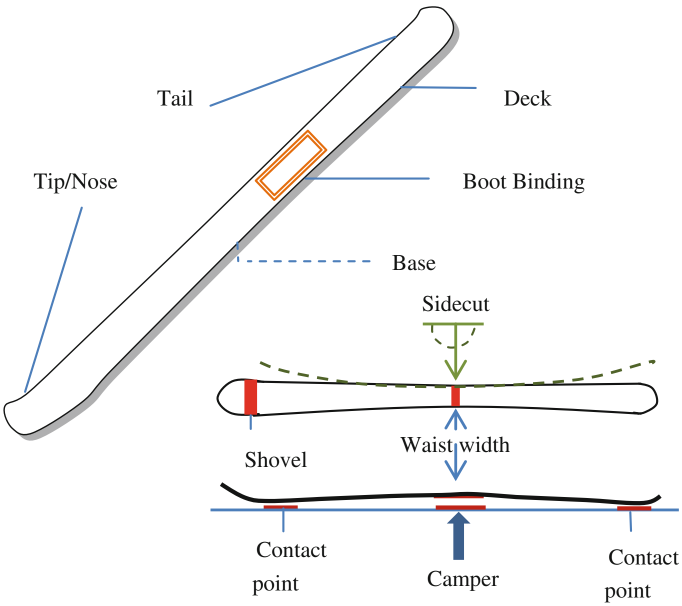

Fig. 1 Downhill skis outer features

- Classic wooden, made out from one single long wood piece
- Laminated wood, made out of two pieces of wood glued together
- Laminated metal and fiberglass, which uses laminated wooden core with aluminum or fiberglass housing sheets
- Torsion box, which has wooden core that has initially been wrapped in wet fiberglass
- Cap design (also called single-shell), where the wooden or foam core is housed in all three sides of the ski in plastic cover.

After the design layout is chosen, the layering of different materials begins. By mixing and layering different materials, the skis are made to perform better various kinds of tasks and they will have very specific characteristics. The outer features of skis, as illustrated in Fig. 1, have the last say in the matter of overall handling, but whether the skis are required to perform hard and quick turns or float the skier on top of a very powdery snow, the inner layers make the performance sustainable. The layers act in many ways, e.g., stiffening or reinforcing the skis, but they also carry a graphical significance when finishing the product according to customer specific details.

In Fig. 2, the molding of ski is illustrated where all the layers with different materials come together and form the actual skis. Depending on the manufacturing process style, the skis can still take part in many different sanding and grinding

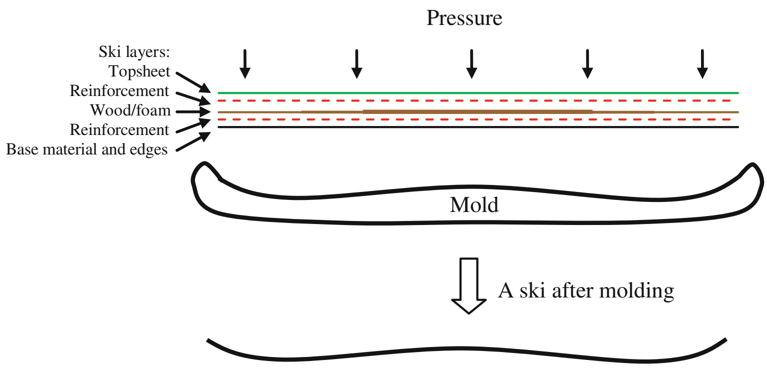

Fig. 2 Ski materials in molding process

operations after the heat molding has been done. Some methods also leave the graphical decals installation to the end phases though usually they are done before molding.

3 Configuration Process

The manufacturing of modern skis has significantly changed from the artisan workmanship of the old days to mass production of today's commercialism. Mass production has pushed the cost and efficiency to their limits, but there is still demand for more personalized and customized products [6, 18]. Because of this reason there still are companies that make high-end skis with custom tailoring almost totally by hand, arguing that their way of doing retain the best of artisan know-how and quality not easily achieved using other construction methods [19, 20]. The downfall with this kind of workmanship is usually both delivery time and price of the final end product.

In article [8], a design configurator has been suggested as a solution for the challenge of bridging pure customization closer to mass production and hence mass customization [21]. To better understand this notion, we next concentrate on the configuration process of such configurator by examining the illustrated downhill skis case example.

One possible representation of a generic configuration process is shown in [22] where the overarching process consists of three temporal interdependent phases; commercial configuration process, commercial configuration, and technical configuration. The starting point is the customer's supply of initial information about the product specification needs which then initiates the activity where all the information negotiated "identify the complete and congruent commercial description of the product that best fits the customer's requirements" [22]. The second phase, commercial configuration, illustrates the specific features and

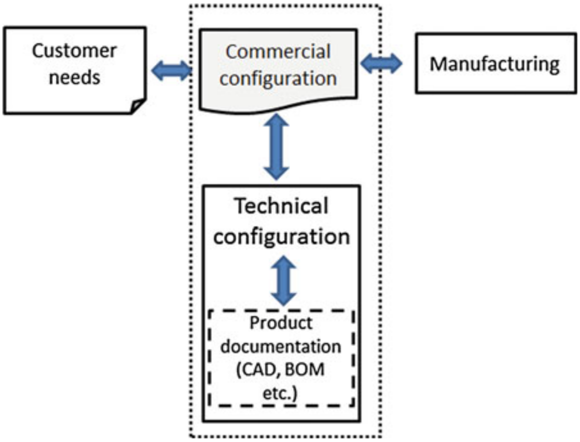

Fig. 3 Design configurator configuration process

characteristic of the product, which the customer is willing to buy and the seller is willing to sell. After this, the technical configuration can be generated where the commercial description of a product is used for the creation of product documentation of such product variant [22].

Though generic this configuration process, as illustrated in Fig. 3, does not entirely apply when we consider the configuration process of a downhill skis with design configurator. The main reason is that all the configuration activities happen inside the design configurator, which now controls the process and guides the user to best satisfy his needs on the ski product.

When the user first initiates the configuration process, he inputs physical details of himself like weight, height, and foot size into the configurator. This denotes the start of the commercial configuration. The user then starts to define the performance characteristics of the skis by selecting appropriate ski design on which the configurator helps the selection. This can include features like the environment (powder, alpine-touring, etc.) or skill level of the user.

This kind of configuration highly resembles the features of sales and product configurator, and it can be argued that design configurator actually performs as one complete configurator but it also depends how the strict definition is made. For example, [23] give three alternatives for sales configurator operations: structure based, feature focused, and performance focused. A design configurator may adapt various function logics but is highly depended on the information systems environment.

After the first configuration decisions, the user starts the main phase: technical configuration. The technical configuration process of downhill skis can be divided into three larger steps:

- Selection of the base construction design of skis: Laminated, torsion box, or single-shell type
- Applying different material layers according to base ski design
- Choosing the outer feature design by performance characteristics illustrated in Fig. 1.

When the user selects, modifies, and tests the skis design, by applying various layering materials like reinforcement metals or fiberglass pieces, the configurator guides the process by offering different setup combinations. It also limits the illegal positions and materials defined by the underlying decision logic in the configurator. These steps are further divided into smaller decision points where the more detailed materials and measurements, e.g., geometric information are given for the product but for the purpose of this simplified example they are not exhaustively listed here.

The fundamental factor with this configuration process is the uses of parametric models, which enable the configurator create new CAD drawings based on the user given data and also construct the normal product documentation (bill-of-materials among other things) on the go. This means that the configuration enables almost infinite variations within the defined borders of the product specifications, which have been parameterized. This is completely different from the basic modular design of selecting only ready-made components from some component library into the design. After all required features have been listed and attached, the product is then ready for the configurator to push to manufacturing which handles the end production according to the specific product documentation details created by the design configurator.

4 Requirements for Information Systems

In the literature, there are few practical examples [8–10] as well as proof-of-concepts [10, 11], which show steps toward more comprehensive and complete design configurator solution. These examples usually show only part of the whole configuration process discussed in Section 3, thus lacking the connection to fully incorporate a true design configurator. From a closer analysis of the configuration process of the downhill skis example, we can now present the information systems integration requirements for a fully operative design configurator.

The requirements can be divided into five distinctive parts. First is the need for visual configuration interface toolkit which acts as the window for the whole configuration process. Similar application concept can be observed in [8, 10] (Asoma Studio case) where both toolkits rely on web browser functionality for their visualization framework. This framework is then used to communicate all the user manipulated data through the second requirement: main configuration process manager based on appropriate logic engine. The purpose of this process handler is to work much like the expert system in [11]. The difference is that the knowledge is shared between different systems and the logic engine determines needed actions between systems and configuration decisions. This possesses the requirement of interoperability of different systems where the process manager is also able to launch and operate other systems.

In the next phase of the configuration process, the customer is seen to start the definition of skis technical specification. He needs to modify the structure,

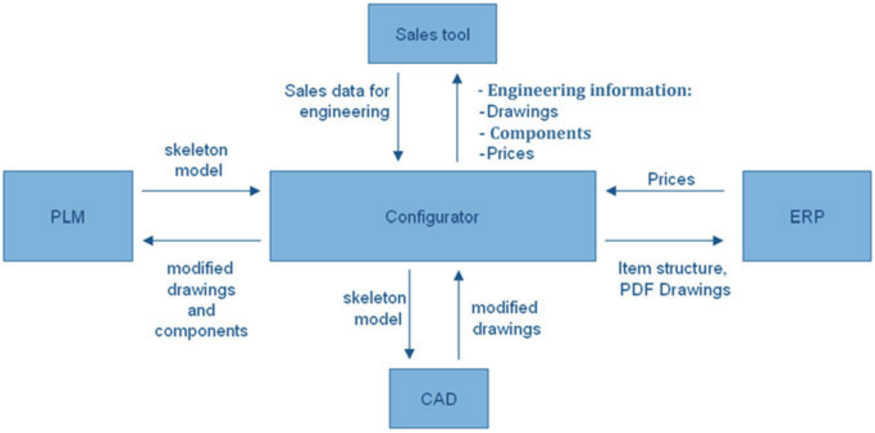

Fig. 4 Design configurator integration schematic

geometrics, and possibly other item details which now raise the third requirement for the IS integration, parametric skeleton model platform. There are many different ways to implement such a knowledge repository, and one suggestion has been an integrated PDM system for product configuration concept [24]. In this example, the PDM platform would also include the logic rules for the overall process handling and configuration management. Other example is the Cargotec MacGregor case [8] where PLM is used only to store the skeleton model information and then the final product documentation. This includes the history data and changes to the model variants. This leads to the fourth requirement of product variant and compilation of product costs for price formation. This can be done via ERP which would then contain the cost information for all the items, materials, and work needed in the skeleton models, product variants, and final documentation (e.g., BOM) of the end product [25]. The last requirement is the interface integration to CAD system. When the user changes details of the product through the visual configurator interface process manager launch and operate the CAD system to provide efficient and accurate depiction of the product and communicate the changes through the logic engine to both model storage (e.g., PLM or PDM) and manufacturing systems (e.g., ERP). Illustration of this requirements schema is shown in Fig. 4.

The final connection to manufacturing happens from the central logic rules system which will send the final customer modified product to physical construction when examining the skis example.

5 Conclusion

Technological development extends the possibilities of efficient customization. A concept of design configurator is suggested to extend the use of configurators to order engineering. Previous research has elaborated on the concept, showed some proof-of-concepts and partial operational cases. However, both research and practice is still in its infancy.

In this paper, we examined the information systems and integration requirements that the concept of design configurator necessitates. For the illustrative case example, we found five major areas that the design configurator must master:

1. visual configuration interface,
2. configuration process manager,
3. management of CAD skeleton models and product variant data in PDM/PLM,
4. compilation of cost information from ERP and manufacturing orders, and
5. interface integration to CAD to manipulate drawings.

With capabilities in these five areas, a design configurator is able to master whole process of commercial and technical configuration and provide accurate and detailed tenders and manufacturing orders, without the need for manual intervention. Yet, practical implementation of such configurator might generate new, so far unrevealed requirements.

Further research is suggested to contribute our understanding of technical requirements and solutions of design configurators as well as business benefits and organizational consequences of utilizing design configurators in various contexts.

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Designfunding: An Inquiry Tool for Mass Customization

Matthias Kulcke

Abstract Designfunding is defined as a unique category of crowdfunding. It is described and explored regarding its potential to become a major inquiry tool for the preliminary gathering of data as a basis for the conception of mass customization products.

1 Introduction

Crowdfunding for designers of furniture and accessories, a special chapter in the comparatively young story of crowdfunding as a means of gathering financial and ideal support for the realization of product ideas, has not yet reached the status of a mainstream technique. This is due in part to the fact that crowdfunding, though repeatedly reported on in mass media, has not yet gained a steady foothold with customers as an online sales tool in all the market areas one could theoretically think of applying it to. Frontrunner products displayed in crowdfunding platforms are projects concerned with accessories and gadgets for, in a lot of cases well spread and well known, brands in information technology [9]. Film projects, as another example, are also frequently crowdfunded and successful with this format.

Crowdfundings, labeled by the project-starters themselves or the administrators of the chosen online platform as belonging to the category of design, appear not to be very successful if dealing with interior design objects. To explore possible reasons and maybe even overcome some of them, the author initiated in spring 2013, in a cooperation with the Institute of Applied Building Technology of the Hamburg University of Technology (TUHH), the Hamburg Kreativ Gesellschaft mbH, and the Hamburger Möbelkooperation, the launch of a contest under the

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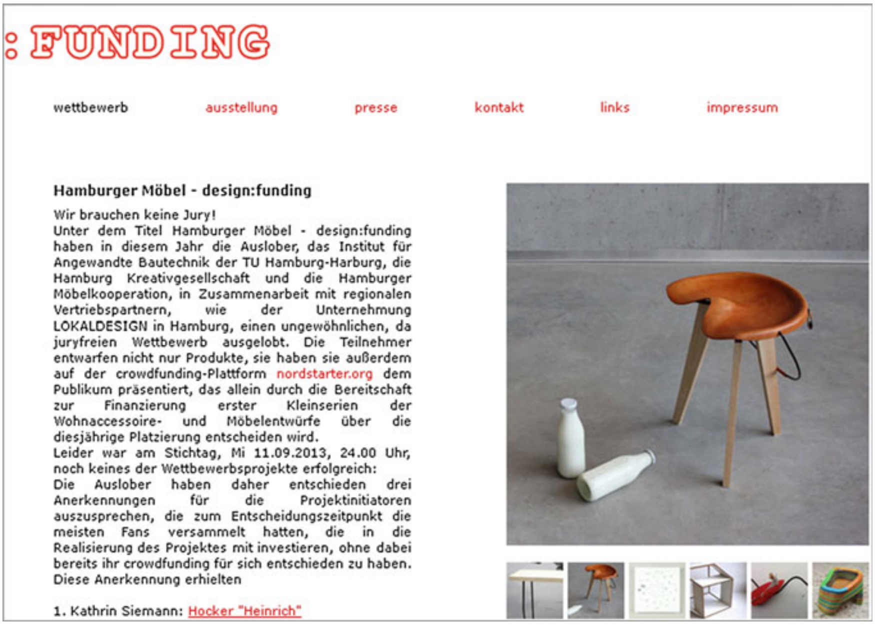

Fig. 1 Contest Web site on www.designfunding.com (detail)

label designfunding. Strategies, pursued to better the chances of the participating designfundings, were the display of prototypes in cooperating stores (stilwerk Hamburg and Lokaldesign), setting up a designfunding Web site (www.designfunding.com), showcasing the designs, and linking them to the crowd-funding platform, as well as an accompanying special exhibition at the stilwerk Hamburg toward the end of the financing phases of the projects (Fig. 1).

The outcome sadly strengthened the original thesis by a collection of only 60 % of the needed sum by the most successful project, considering percentage of the projected budget [2]. A preceding search through www.kickstarter.com and www.startnext.de undertaken by the author showed comparatively few crowdfundings in the category of furniture design and a slim margin out of those in the category of successful projects.

Although it has to be stated, this does not imply that they are least likely to succeed overall and, in the long run, since there are product groups that are not represented at all in the present or past crowdfunding campaigns. There are designers who already use this format, and if the formats used by designers were to be optimized, more are bound to get their campaigns fully financed.

The crowdfunding technique is generally on the rise [6] and to be reckoned with, and it is very likely one of the suitable means in the future to reach potential and actual customers with a new design product, which is not particularly connected to information technology. The frequent launching of specialized crowd-funding platforms, such as www.technofunding.com and www.sciencestarter.de, is a further indicator that crowdfunding is here to stay and will further spread into the conscience of the consumer. In the fall 2013, the regional platform www.dutchdesignstarter.com [5] was launched as a designfunding platform for Dutch designers and residents. At the time of this writing, there were no successful crowdfundings yet listed in the category of furniture design.

2 Crowdfunding Phases and the Integration of Crowdsourcing

The three phases of a crowdfunding, and thus for a designfunding as well, are labeled broadly: preparation or pre-campaign, starting phase, and financing or fundraising phase. Some platforms do not require a starting phase and some describe a conclusive or post-campaign phase as what is to be done after a successful funding [7].

2.1 Preparation or Pre-campaign

In preparation, the content of the personalized crowdfunding page is developed and successively uploaded, in the best case accompanied by productive feedback from the administrators of the platform. The crowd, for better chances of success, should be pre-gathered, with the help of social networks such as Facebook and Twitter.

2.2 Starting Phase

The starting phase is not mandatory on all platforms; it can be included in the financing phase. The project-starter goes public and invites people to become fan of the project and of course the product. It is especially in this phase that the project-starter enters also a potential crowdsourcing phase. Crowdsourcing has of course already been spotted by a lot of enterprises as a tool to optimize products by putting their clients to work [1], even valued to the degree that the firms are willing to pay for such information, having its provision offered as a service to them by specialists [4, 8].

Since new products are developed, and sometimes not even a first prototype has been produced before a first series is financed, the products advertised in a crowdfunding campaign are still subject to change. This is not only due to the nature of the format; it is also something skilled designers and entrepreneurs are aiming for, as part of the design process. Invitations to make a contribution to the project blog, considering the appearance and functions of the final product, are posted and automatically spread by email newsletter to those registered to the platform and who also chose to hit the fan-button of the project. This serves on the one hand to remind fans repeatedly of the ongoing campaign, to hopefully increase their willingness to financially support the project and at best to become customers by choosing the product itself as an incentive for their monetary contributions.

Now, these interactions with supporters, already vital to designfundings in progress, might even be extended and/or specified targeting something else: the collection of substantial data as a base for deciding upon fixed and variable parameters of a future mass customizable product series that is to be developed out of the approach to the market through the designfunding campaign. This goal is probably more likely to be reached if the initial product concept includes a mass customization strategy, but it might also spawn from a designfunding that did not aim for mass customization at first and is then changed according to customer responses pointing in this direction.

Taking these possibilities into consideration and integrating them in campaigns could not only further establish designfunding as a marketing tool for new mass customization products, but also serve as "radar," scrutinizing their chances of success with customers.

2.3 Financing Phase or Fundraising

Even in the financing phase, further relevant information concerning customizability can be collected, by analyzing which product configuration is preferably chosen from the list of incentives presented to the customers who order them. And, since it is possible to list additional incentives even while already in the financing phase, a campaign-starter can react to fine-tune and adjust favored product configurations, without having to alter a production, because production only starts after the fully financed designfunding has come to a conclusion.

3 Parametric Design in Crowdfunding

Parametric design with the aim of mass customization is characterized by a mix of fixed and variable parameters, chosen by the designer preceding the programming and launching of a permanent sales platform including the configurator, which establish the product-specific mass customization strategy. The image below shows an overview of how a parametric design process may be enhanced by adding cycles to the iterative design process, including data gathering through a designfunding (Fig. 2).

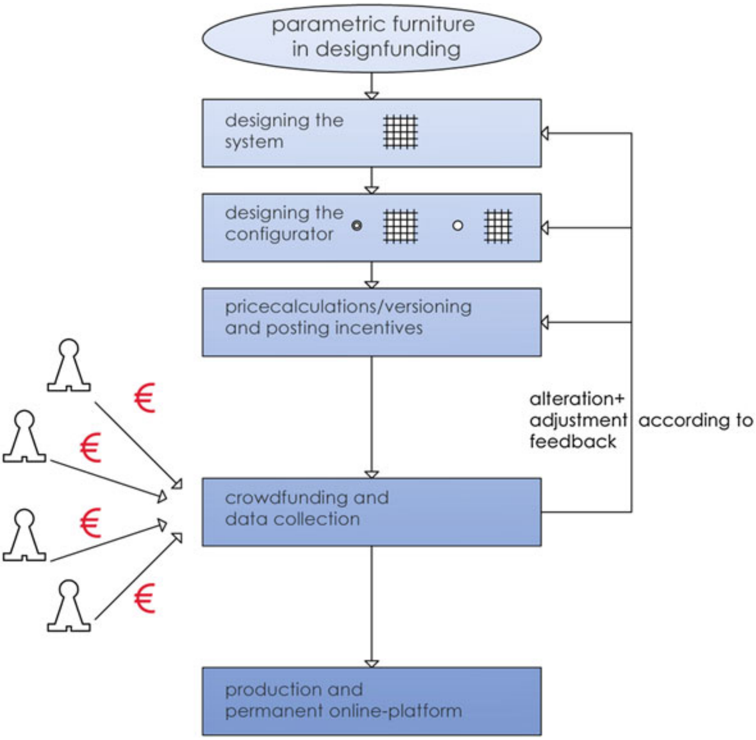

Fig. 2 Connecting the design process of MC products with designfunding

4 Conclusion

In particular, design products for production in small numbers by regionally active craftsmen and manufacturers are suited for this market approach, since cost-intensive prototype production can be minimized and focused on the most promising pre-configured constellations in the case of a successful funding. Although the recently released Indiegogo Hardware Handbook advises campaigners to build works-like and looks-like prototypes, it is, according to the contributors, not vital for a campaign to build design-for-manufacturing (DFM) prototypes [3]. The same goes for the development of the user interfaces and integrated configurators on the succeeding permanent online sales platform for the mass-customized product, because variable parameters to be selected by the customer have already been sent through a cycle of testing in a direct dialogue with buyers (for a realized example following a crowdfunding, see [10]).

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Does Customer Co-creation Really Pay Off? An Investigation into the Firm's Benefits from Customer Involvement in New Product and Service Development

Marcel E. A. Weber and Dirk H. Van der Laan

Abstract The active involvement or co-creation of customers in the innovation process is nowadays very common for firms. Since the awareness that it also entails the involvement of customers, many organizations have taken this step. Customers are nowadays assailed by firms' requests to participate in co-creation challenges, crowdsourcing invitations, and so on. Until now research has mainly focused on the question why customers indulge on such requests and what they get out of these participations. However, little attention has been given to the benefits firms reap from co-creation initiatives. This research tries to bridge that gap and investigates the outcomes organizations perceive from co-creating with their customers. Through a research data on the employment of co-creation by 154 Dutch organizations, we investigate how this co-creation affects innovation success, financial results, reputational results, and organizational benefits. Compared with organizations that do not co-create with their customers, organizations engage in co-creation benefit better from these efforts, culminating in more successful innovations, an increase in business reputation and an increase in organizational capabilities. However, customer co-creation does not seem to have a better effect on the financial results.

Keywords Open innovation · Customer co-creation · Innovation success · Customer involvement in NPD and NSD

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1 Introduction

Companies ask a lot from their customers these days. In addition to purchasing products and consuming them, customers may be expected to forgive negative experience [1], pay premium prices [2], and make loyal purchases [3]. Customers are encouraged to attend brand-centered events [4], participate in brand communities [5], and communicate with other customers of a brand [6]. Companies ask their customers to spread word of mouth [7, 8], participate in research [9], volunteer time [10, 11], and donate money [12, 13]. Firms seem to benefit from such actions even though they do not take the customers' benefits into account [14]. It is argued that customers try to create a meaningful relationship with brands that is qualified by the perceived ego significance of the chosen brands that adds meaning to people's lives [15].

In the past decade, a new way of customer participation has risen: customer co-creation. Customer co-creation entails the active involvement of customers in the creation of new value for firms [16]. As it can be derived from its name, it is evangelized that customer co-creation is beneficial to both firms and customers in several respects. The benefits for customers when participating in co-creation have been researched extensively, both conceptually and empirically, e.g. [17–21]. However, for firms, it is only assumed and argued that co-creation with customers holds benefits; we lack systematic empirical evidence for the fact that the sourcing of external knowledge from customers is beneficial for a firm [22].

To close this gap in research literature, we integrate theoretical insights from literature on co-creation to develop some hypotheses on firms' benefits from customer co-creation. To test these hypotheses, we examine the effect of customer co-creation on several business performance outcomes in a survey on the customer experience and co-creation efforts of 115 firms in the Zwolle region of the Netherlands. We evaluate the correctness of each hypothesis and conclude this paper by mentioning several limitations to our research.

2 Theoretical Base and Hypotheses

Open innovation assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as the firm look to advance their technology [23]. Companies can no longer focus only on efficient intra-organizational knowledge creation and sharing, but should also include the inter-organizational realm, as well as other relevant stakeholders in its business ecosystem, like various start-ups, universities, research consortia, incubators, and other outside organizations [24]. To survive and thrive in an increasingly turbulent landscape, it has become necessary to create new relationships and new mental space with diverse members in the sociocultural business system that includes employees, partners, suppliers, competitors, and most importantly, customers [25].

Customers know more about their context, their desired outcomes, their needs, and their constraints than firms can ever hope to learn [26], making them an almost not to be neglected source for firms that decide to undertake the journey of open innovating [25].

Von Hippel [27] asserts that users are a powerful source for innovations. Involving customers in the innovation process can be beneficial for firms, in the case of developing new products for business users [28, 29] as well as consumers [30] or for new services [31, 32]. The contribution of customers is growing steadily larger as a result of continuing advances in computer and communications capabilities [30].

2.1 Innovation Success

Firms have a great deal to gain from involving the user in the design and development process, both in its pre-launch phase (initial innovation) and in its post-launch phase or re-innovation stage [33]. Firstly, manufacturers can complement their own R&D efforts through plugging into the technical strengths of their customers. Secondly, involving the user is a great aid to establishing the optimum performance/price combination, which in turn establishes the optimum design specification. Thirdly, involved users undergo a learning process that enables them better to operate the new equipment when it is installed, making such users potential demonstrators for potential customers of the innovation. This learning effect also applies to new services that are developed with customers [34]. This can, in turn, accelerate the acceptance process from new designs [35]. Finally, the good relationships engendered through user involvement in the formulation of the initial design can result, if maintained, in a flow of user-initiated improvements, thus extending the equipment's life cycle [36].

User involvement during NPD can therefore be beneficial for two reasons. First, the quality of the product is improved by incorporating users' mental schemes [37] and their specialized needs and preferences [27]. The manufacturer may develop a product that better fits user needs [28, 38, 39]. Even, when new services are developed, customer involvement may lead to successful new services with unique benefits and better values [34]. Second, users are more receptive to a new system if they contribute to its design [35, 40]; involvement may accelerate market acceptance and diffusion of the product [28] and new service [34]. User involvement per se does not result in the realization of systems benefits. It is the accommodation of mutual needs identified during user involvement that is important [41]. A better product or service, new value to the customer, greater market acceptance and diffusion are all elements of a successful innovation, so we can state our first hypothesis:

H1 *Co-creating with customers in innovations will lead to successful innovations, entailing a better fit to user needs, faster acceptance and diffusion of the innovation*

2.2 Financial Results

Smedlund [42] argues that user involvement is likely to result in high profit combined with a lower and shared risk of failure in the development process. Involvement of the user helps to establish the optimum price/performance combination [43]. Syam and Pazgal [44] demonstrate that if firms charge a single price over price differentiation for co-creation settings this self-imposed lack of pricing flexibility may actually be profit enhancing. Franke and Piller [39] and Schreier et al. [45] assert that the value that customers perceive of co-created products is higher than the price of firm-created goods, resulting in an opportunity of exclusive pricing and higher profits. A study concerning the involvement of lead users at 3 M [46] argues that annual sales resulting from this involvement are conservatively projected to be more than eight times higher than forecast sales for the average contemporaneously conducted traditional project. Co-creation can lead to growth, increase in share value, and increase in profits [47]. Involving potential users in the process of product development, the manufacturer may shorten the duration of the total development project [28], resulting in the reduction of development costs. We can therefore conclude with the observation that co-creation has a positive effect on the financial results, consisting of a higher profit, turnover, and sales, in combination with lower costs, for a firm:

H2 Co-creating with customers in innovations will lead to increased financial results for the firm

2.3 Reputational Results

Developing products that meet customers' needs and preferences because they were involved could mean that customers will be better satisfied than when they are not involved [39]. Co-creation with customers will increase customer satisfaction [48] and loyalty [33, 34, 49–55]. Mäkipää et al. [56] found in their research that when seeking to increase customer loyalty and attracting new customers, companies need to increase customer involvement in research and design operations. Another advantage for customer involvement in new service development is the improvement of long-term relationship with customers [34, 57]. A company's reputation, resulting from an increase in customer satisfaction, loyalty, and relationship, will prosper when the company co-creates with its customers:

H3 Co-creating with customers in innovations will lead to increased reputational results for the firm

2.4 Organizational Results

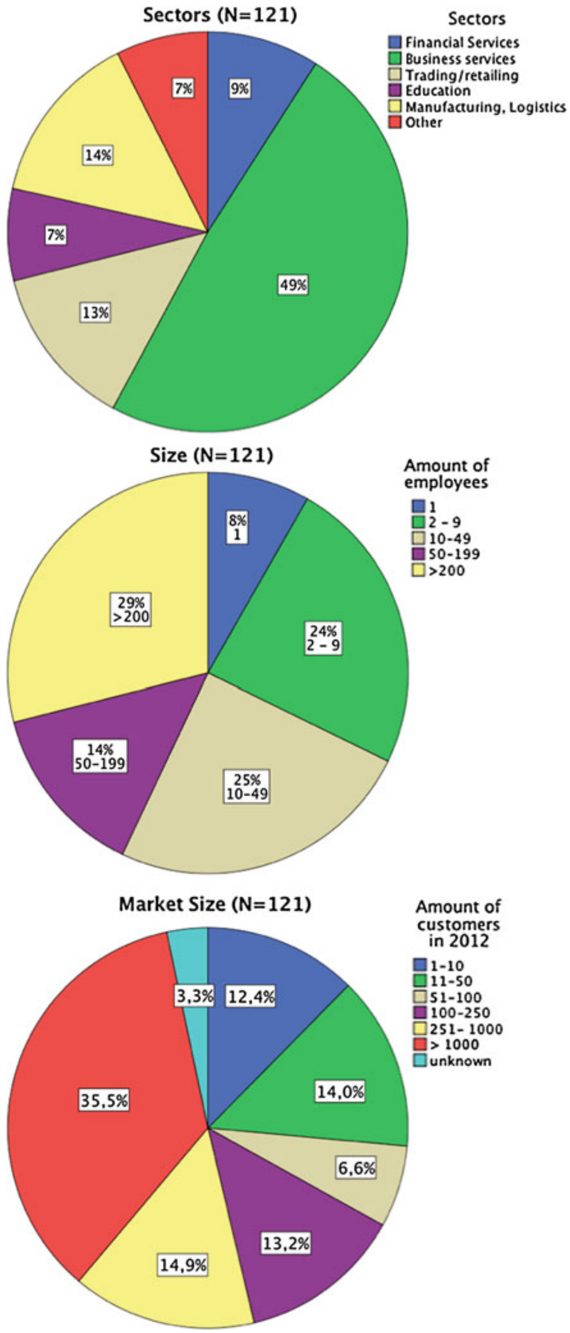
From the perspective of the firm, customer involvement in innovations offers information valuable in achieving ideal costs and time in production [58] and in reducing the uncertainty during the innovation process, such as those regarding the environment and user demands [35, 59]. Co-creation with customers can improve the effectiveness of the product development process [60, 61]. Customer involvement can be important for decreasing development time [35, 62–66], which is especially useful in incremental innovations [58, 67]. Development time has become particularly important in development in order to secure competitive advantage [68, 69]. Moreover, innovation speed has been shown to be the most appropriate measure of success in highly competitive and rapidly changing markets with short product life cycles [70, 71]. By involving customers in an early stage in a continuous way, the product development process may be accelerated [72]. By involving potential users in the process of product development, the manufacturer may shorten the duration of the total development project [28]. Another advantage for customer involvement in new service development is reduced cycle time [34, 73, 74]. Chien and Chen [75] discovered that customer involvement is beneficial to cross-functional integration during the NPD process as well, because it confronts different departments that have differing viewpoints on the process or its outcomes with an independent party reducing controversy. Furthermore, customer involvement can inspire the innovation process of the firm [73]. Chan et al. [48] show that co-creation with customers also drives performance outcomes like employee job satisfaction and employee job performance through the creation of economic and relational values. So we can posit our last hypothesis on the internal organizational results, entailing a higher employee satisfaction, an increase in productivity and innovation capacities, and a shorter time-to-market.

H4 Co-creating with customers in innovations will lead to increased organizational results for the firm

3 Data Acquisition Method

To test the hypotheses, we conducted a survey among organizations in the Zwolle region of the Netherlands. The survey, the customer experience and co-creation monitor, was designed to investigate the use of both customer experience management and co-creation by respondents. The participating organizations varied in size, sector, and market size (Fig. 1). The research was conducted in the second quarter of 2013. About 800 organizations were invited to participate in an online survey on their efforts and benefits in customer experience management and

Fig. 1 General data on respondents (valid: 121)



customer co-creation; 154 responded by filling in and returning the survey, of which 141 were valid. Since it is our aim in this article, we will restrict our current analysis on the results of the co-creation efforts and leave out other results of the survey.

In order to limit the amount of survey questions and time invested by respondents, the constructs being tested were measured by asking the responding manager for his/her perception of the change in the mentioned outcome: Has the outcome increased or decreased since the start with their efforts on co-creation. These outcomes were as follows: innovation success (H1), financial results (H2), reputational results (H3), and organizational benefits (H4). The relevant questions were all stated in a 5-point Likert scale. Although this would lead to subjective results, we refrained from asking for objective proof for the change in outcomes, since it is our intention to perform follow-on research in qualitative interviews, on the exact impact of co-creation—and other—efforts on the business results.

4 Results

From the 154 respondents, 72 (46.7 %) indicated that they took action to co-create with their customers in NPD or NSD; 34 (22.1 %) indicated that they did not co-create at all. The rest (31.2 %) are not aware of any co-creation actions or initiatives within their organization and were therefore excluded in this research, leaving us with two samples: co-creating and non-co-creating organizations. From the remaining 96 organizations, 14 refused to reveal the financial, reputational, and organizational benefits from their co-creation efforts. Table 1 provides the descriptive results on these four variables. It can be observed that regardless of the fact that the organization invested time and effort in co-creation, the majority of respondents signaled an increase in all four variables: innovation success, financial results, reputational results, and organizational benefits. Based on these data, we can therefore not conclude that co-creation with customers is more beneficial than not co-creating with them. Although this amount of 82 respondents looks rather small, we nevertheless tested our four hypotheses, claiming that it is more beneficial to co-create than not to co-create. To execute this test, we compared the two samples (organizations which co-create and organizations that do not co-create at all) with the Mann–Whitney test on the four designated outcomes of co-creation. Table 2 shows the results of this Mann–Whitney test, revealing significant differences between co-creating and non-co-creating organizations for innovation success (H1), reputational results (H3), and organizational results (H4). We therefore accept these three hypotheses, with the addition that co-creating organizations benefit more than non-co-creators. On the other hand, financial results resulting from co-creation are not higher than for non-co-creators, implying that H2 is rejected. This is not so surprising since there are many other factors that influence the financial results from new product introductions [76], which were not accounted for in this research.

Table 1 Co-creation outcomes for co-creators and non-co-creators

		Very unimportant	Unimportant	Neutral	Important	Very important	Total
How important is co-creation for your organization	Co-creators	6	0	4	35	28	73
	Non-co-creators	0	2	15	15	2	34
		Totally disagree	**Disagree**	**Neutral**	**Agree**	**Totally agree**	**Total**
Co-creation with customers leads to successful innovations	Co-creators	1	7	18	33	13	72
	Non-co-creators	2	1	23	7	1	34
		Strong decline	**Slight decline**	**Unchanged**	**Slight increase**	**Strong increase**	**Total**
Financial result from co-creation	Co-creators	3	9	25	22	11	70
	Non-co-creators	1	4	7	7	3	22
		Strong decline	**Slight decline**	**Unchanged**	**Slight increase**	**Strong increase**	**Total**
Reputational results from co-creation	Co-creators	3	9	25	22	11	70
	Non-co-creators	1	4	7	7	3	22
		Strong decline	**Slight decline**	**Unchanged**	**Slight increase**	**Strong increase**	**Total**
Organizational results from co-creation	Co-creators	0	5	18	38	9	70
	Non-co-creators	0	2	11	8	1	22

Table 2 Mann–Whitney test results

Result of the Mann–Whitney test on customer co-creation outcomes

Variable	Co-creators			Non-co-creators			Mann-Whitney U	Asymp. sig (two-tailed)
	N	Mean	Std dev.	N	Mean	Std dev.		
Innovation success	72	3.69	0.929	34	3.12	0.769	759.5	0.001
Financial results	70	3.41	1.042	22	3.32	1.086	732.5	0.72
Reputational results	70	4.1	0.705	22	3.59	0.666	452.5	0.001
Organizational benefits	70	3.73	0.779	22	3.36	0.727	560.5	0.037

5 Discussion

5.1 Co-creation is Beneficial to Organizations

As expected, organizations, which co-create with their customers, benefit from this. Compared to organizations that do not co-create at all with customers, these co-creating organizations perceive better success, increase in their business reputation, and improved organizational capabilities. Although we detect no difference between co-creators and organizations that do not engage in co-creation in the perception of the change in their financial results, reported financial results did increase, indicating that co-creation does not have adverse effects on financials. That we did not encounter a significant difference between the two researched groups can be attributed to the fact that financial results are dependent on other influences as well. More and detailed research is needed to establish the factual impact of co-creation initiatives on these financial results.

5.2 Limitations

As with many empirical investigations, this research also entails several limitations, preventing us from generalizing the results. First, response is low compared to the total population, raising questions about the representativeness of the results. Although the Mann–Whitney test clearly demonstrates superior results for co-creators compared to non-co-creators, where the ratio of co-creators to non-co-creators is approximately 2 to 1, this research cannot conclude that co-creation is the only or main cause of the better results. Neither can we state that about two-thirds of all regional organizations engage the customer in co-creation. Increasing the number of respondents may provide more reliable figures.

Furthermore, the result variables (innovation success, financial results, reputational results, and organizational results) have been measured through self-reporting of the respondents on superlative measures, entailing subjective views, meaning as much that one's perception of, for example, a "strong increase" or "strong decline" can differ from another's. The research could be enhanced by providing more objective classes of measures, e.g., "25 % increase or more." It is our intention to further investigate the exact impact of co-creation efforts on these result variables.

Finally, we have aggregated several single result constructs into four result categories—innovation success, financial, reputational, and organizational capabilities—and based our conclusions on the measurement of these four categories, without investigating the effect of the single result constructs on the categories. An increase in turnover may, for example, coexist with a decline in profit, but how does one classify the financial result: as an increase or a decline? We therefore recommend taking these limitations into account in a following study.

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Enablers of Innovation in the Construction Material Industry

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Abstract The construction material industry is often acknowledged as slightly more innovative than the overall construction industry and could hence serve as a valuable learning place for how innovation could flourish in the construction industry. Construction is viewed as network or supply chain based, which creates a strong interdependence between the different supply network partners and can be seen as a hindrance for innovation. Innovation models must embrace such a contemporary business structures, where competition often takes place between supply chains rather than between individual companies. By exploring case-based innovation processes the purpose is to discover enablers of innovation in the construction material industry. The research design is based on explorative case studies. By applying case study as method, the research is drawn towards inductive research, where we investigate patterns suitable for generalization on enablers for innovation. In total, six cases of successful innovation are investigated. The conclusion of this research validates that open innovation in a network approach is a precondition for a successful innovation journey in the construction industry. In addition, it was found that different approaches for facilitating this journey exists, based on company characteristics. This paper adds to the body of knowledge on

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how to succeed with innovation in the construction industry. The increased awareness of an open and cooperative approach to innovation is of value both theoretical and practical.

Keywords Open innovation · Enablers · Construction materials · Network

1 Introduction

In general, it is recognized that innovation contributes to economic growth of industries as well as competitive advantage of firms [1]. The construction industry is in many countries considered to be a slow adopter of new technology and new processes, and its conservatism and tradition bound thinking pose serious implications for the rate of innovation, which lags behind most other industries, and appear to be falling further and further behind [2]. This is in particular of concern, as the construction industry's turnover typically ranges from 5 to 12 % of a nation's GDP [3, 4]. It is clear that improvements would be highly beneficial not only for the individual firms in this industry, but also at an aggregated macro-economic level. Hence, a dedicated focus on how to enable innovation practices within this industry is important.

The research presented in this paper specifically focuses on the construction material industry, which is considered to be a subpart of the whole construction industry. The construction material industry is often acknowledged as slightly more innovative than the overall construction industry. Pries and Dorée [5] investigated innovations in the Dutch construction industry and found that about two-thirds of all innovations originate from supplying industries. Winch [6] argues that innovation efforts in the industry are disproportionately orientated towards product enhancement rather than process improvement. This corresponds well with the observations of Pries and Dorée [5]. The construction industry is in this research viewed as collaborative networks within a supply chain. This structure creates a strong interdependence between the different supply network partners (suppliers, manufacturers, retail, architects, and construction contractors) and can be seen as a hindrance for innovation [7]. Yet, innovation models must be developed to embrace such contemporary business structures, where competition often takes place between supply chains rather than between individual companies [8].

Even though the construction material industry is more innovative, known for higher gross margins and better earnings than the construction industry in general, improvements are still highly necessary. The construction material industry has often been criticized for not providing added value for the end-user, and for being an additional supply tier adding costs to the final construction. There are two main arguments to narrow the scope for this research to only focus on the construction material industry. Firstly, this industry can provide cases of "successful" innovation. Successful should be perceived as Van de Ven [9, p. 591] wrote "managing ideas into good currency." Since this research aims at identifying enablers of innovation, it is imperative to have access to such cases. Secondly, we argue that the construction material industry can be viewed as an innovation broker for increasing the innovation level of the whole construction industry.

It is largely acknowledged, and underpinned by empirical research, that effective and efficient management of innovation depends on a range of contingencies [e.g. 10–12]. In order to be innovative, firms have to be aware of the specific circumstances influencing possibilities to innovate. Studies have already been undertaken to examine enablers of construction innovation. Yet, a consistent and general understanding of innovation management in construction is still missing [10]. The present research effort addresses this knowledge gap by studying the following question: How is innovation structured and managed in construction material firms that have had noticeable innovation success?

By exploring case-based innovation processes, the purpose of the research at hand is to discover particular enablers of innovation in the construction material industry.

2 Method

The main method is the explorative case study with the purpose of identifying innovation processes and analytic generalization [13]. A qualitative study is preferred due to the lack of consistent understanding and use of innovation in the construction material industry. Malløe [14] argues that an inductive case study is suitable for creating new understanding, amongst others because the expected bias is made explicit.

2.1 Data Selection and Collection

The first step in data collection was to establish a number of criteria for the selection of cases. Rigorous and consistent application of such criteria increases the credibility of the research [15, 16]. The criteria were as follows:

- Should be within the construction material industry. No exact definition of this industry exists, hence it can range from screws and nails to prefabricated bathrooms. However, companies closer to being part of the manufacturing industry have been left out.
- Should be small- and medium-sized enterprises. The European commission's [17] definition of SME's was applied, whereby criteria in terms of employees, turnover, and balance sheet were applied.
- Should not be direct competitors. Instead, the selected companies should represent different subparts of the construction material industry in term of degree of processing.

Table 1 Data collection for each of the six cases

	Semi-structured interviews	Material from archives
Case 1	• Chief executive officer • Product development manager	• Internal notes • Minutes • News clips
Case 2	• Chief executive officer • Project manager	• Business plan • Consortium contracts
Case 3	• Chief executive officer	• Marketing material
Case 4	• Chief executive officer • Project manager from system development	• Internal notes • Marketing material
Case 5	• Head of development	• Consortium contracts
Case 6	• Chief executive officer	• Internal notes

- Should be characterized as being "successful" innovators. This is a very subjective selection criterion. It is operationalized by four sub-criteria, which are discussed below.

It can be discussed how exactly to define and understand "successful with innovation." No obvious measurable figures exist for this purpose. It would be misleading to use, e.g. growth as an indicator for successful innovation, as innovation could be one of several reasons for a company to grow larger, but no coherent relation occurs. An increased turnover is also an inconsistent indicator for successful innovation. Process innovation could lead to a decrease in flexible and/or capacity costs, but several other factors influence these costs. The amount of patents held by the company could be an acceptable indicator for successful innovation, but many innovations are not suitable for processing patents, especially incremental process innovations. Costs allocated to research and development could be a relevant indicator for innovation activities, however, more than often, the R&D costs of an organization is kept confidential and are not displayed in public account reports.

It is, therefore, concluded that no specific and objective quantifiable measures for successful innovations occurs. Instead a combination of less precise selection criteria is applied:

- If a company describes themselves as innovative, it could be an indicator for explicit innovation activities. The degree of success cannot be validated in this criterion.
- Expert evaluation as innovative.
- The media recognizes the company as being innovative.
- The authors' extensive empirical knowledge of innovative companies in the construction material industry.

A total of six cases were selected to be included in the research.

As the methodological strategy for the research is case studies, the primary data collection methods were semi-structured interviews and collecting material from archives. Table 1 illustrates data collection in relation to each case.

Table 2 Selection criteria in relation to each case

Criterion	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Construction material industry	X	X	X	X	X	X
SME						
Less than 250 employees	X (140)	X (11)	X (32)	X (175)	371	X (31)
Turnover max 50 mill euro	X (27)	n/a	n/a	n/a	150	n/a
Balance sheet max 43 mill euro	X (9,8)	X (0,7)	X (1,2)	X (37, 8)	692	X (2,8)
Product	Prefabricated	Roofing	Heating	HVAC	Cement	Precast
Successful innovator						
Own statement		X	X	X	X	X
Expert statement	X	X	X		X	X
Media statement	X	X	X	X		X
Authors knowledge	X	X	X	X	X	X

2.2 Presentation of Six Selected Cases

Six cases were applied for data collection in this research. Since all six companies are based on the Danish construction material industry, full anonymity was granted.

Selection criteria for each case are summarized in Table 2 and commented upon afterwards.

Case 1 is a highly automated and industrialized producer of modular box-based houses and cottages. For several years, they have been seeking to optimize their production process by, amongst other things, introducing LEAN manufacturing. They do not perceive themselves as innovative (the term innovation is not well seen by the CEO), instead they: "*…just follow good ideas.*"

Case 2 is a young firm with a fully outsourced production. They collect production scrap and waste from wind turbine production, plastic production, and glass production. These raw materials are used to produce composite panels, isolation panels, roofing panels, and sound insulation panels.

Case 3 is a manufacturer of high-end design radiators and other heating systems. For the past couple of years, they have integrated user-driven innovation principles in their design process, resulting in, amongst others, a radiator laboratory where architects can come and "play" with radiator components and build their own design.

Case 4 produces advanced HVAC systems. Each year, they host a "ventilation innovation day," which is open for all interested parties. They have an open innovation agenda and have also founded a special R&D subdivision with the primary purpose to stay in contact with high-ranked university research in the HVAC field.

Case 5 is a firm-producing cement products. It is a very large firm and should hence not have been selected due to the SME criterion. However, this case is still relevant because it is known for owning many patents and develops new products in accordance to a highly structured innovation process. It is also well-known that this firm actively strives to change the boundary condition, both politically and legally. From Table 2, it shows that case 5 does not match the SME criterion. However, the number of employees is not exceeded significantly. The case is included due to the fact that this case is placed upstream in the construction material industry's supply chain, i.e. the degree of processing is very low. In total, it can be concluded that one large, two medium, and three small companies are presented in this study.

Case 6 is a 10-year-old firm-producing high performance concrete solutions, specializing in sleek balconies and staircases. They perform a very active marketing strategy, branding themselves as highly innovative.

The six cases represent different products with different degrees of processing, ranging from case 1 prefabrication of modular boxes to case 5 cement production. This enables a broad picture of innovation structures and management in the construction material industry.

2.3 Data Analysis

The data analysis is executed as a comparative analysis of the six cases with respect to specific subjects. These subjects were defined as conceptually relevant guidelines for conducting the case studies. The subjects were all confirmed through the qualitative dialogues as being of high relevance the innovation activities of the case companies.

- Scope of innovation. Identification of which scopes are applied in the innovation processes, namely product, process, organization, market, or technology.
- Open innovation. An analysis of how open each company is in their innovation process, and a description of who they involve, e.g. customers, consultants, supply network, or external cooperation (with competitors).
- Innovation maturity. An adaption of Essmann and Du Preez' [18] five levels of innovation maturity is applied to identify how mature each case is in terms of innovation activities.

For each subject (scope of innovation, open innovation, innovation maturity), the data analysis is based on interviews and data from archives. To present the data and conclusions in a condense form different schematic approaches are applied, e.g. spider diagrams. The values used in spider diagrams are developed through a qualitative measure of percentage, which allows for the identification of patterns across the six cases.

3 Findings

3.1 Scope of Innovation

In order to identify the different scopes of innovation, we return to the very basics of innovation theory. Schumpeter [19, 20] described and distinguished between five scopes for innovation known as: products (or services), processes, technology, exploitation of new markets, and new ways of organizing [21]. Similar scopes of innovation are still found at the core of contemporary definitions of innovation. Amongst others, this is reflected in the 4P's of innovation [22], (1) identified as product innovation (changes in the deliverables that the organization offers, be that in the matter of products or services); (2) process innovation (changes in the manner of which the deliverables are created and delivered); (3) position innovation (changes in the context or markets in which the deliverables are introduced) [23]; and (4) paradigm innovation (changes in the models and organization, which frames what the organization does) [24]. We hence apply the following five scopes of innovation for the case analysis; product, process, organization, market, and technology (Table 3).

Figure 1 shows that all cases involve from three to five of the five different scopes for innovations. This implies that the companies have a broad access to how to innovate. However, there is a clear indication that not all of the firms are capable of performing technologically driven innovation. It also indicates that synergy arises when innovating with several scopes simultaneously. An innovation of a new product is often based on an identification of several observations and ideas from market request and trends, new technology, etc.

Five of the six companies rate product innovation is very high. Case 1 has high focus on LEAN optimization of the production process of prefabricated construction modules. No connection between innovation scope and degree of processing is observed. However, it is noted that case 1 with the most processed product unilaterally focuses on process innovation. Also, no interdependencies between the different innovation scopes are evident. The only clear observation is the openness towards use of several innovation scopes simultaneously. The findings for the six cases are illustrated on two radar diagrams in Fig. 1 presented.

3.2 *Open Innovation*

How the six cases cooperate with external partners in their innovation activities is illustrated in Fig. 2 and presented.

It is evident that all cases apply open innovation and cooperates with one or more external partners in some degree.

It is a tendency that the cases cooperate in a small degree with consultants. Case 1 differs again. They cooperate extensively with consultants, amongst others in terms of adopting LEAN production principles. All cases cooperate with different Danish GTS[1] institutions. All six cases cooperate with customers in a medium to a high degree. How they cooperate is very different. It ranges from

[1] GTS: Advanced Technology Group is a network consisting of nine independent Danish research and technology organizations approved by the government.

Table 3 Scopes of innovation

Innovation scope	Product	Process	Organization	Market	Technology
Case 1	Prefabricated elements applied to optimize production	Flexible production. Lean and systemic optimization	Transparency in production. Conscious of own abilities and where other capacities are needed	In-house workshops to generate ideas for facing new challenges in market	Automation of production via robotic solution
	Collaboration with other companies to innovate the product by developing new production forms	Flow alignment	Consultancy involved to support expansion		
	Both proactive and reactive approach within incremental innovation	Ad hoc and long-term decision making	Vertical collaboration within the organization and across disciplines		
		Open innovation. Strong focus on process innovation			
Case 2	Does not have a fixed product programme	Outsourcing to sub-suppliers	Participating in several networks	Develops ideas based on market surveys	Innovation is based on specialist/engineering knowledge of materials and technology
	Innovation ideas is often based on new supplier products		Cooperates intensively with universities	Applies user-driven innovation	
	Capable of spotting products that support future market needs		Works as coordinating tier between customer and suppliers	Attempts to influence national codes and regulations	

(continued)

Table 3 (continued)

Innovation scope	Product	Process	Organization	Market	Technology
Case 3	Developed a product laboratory where architects can come and experiments with their products	Changed their CAD program to be consistent with market trend	Has several times hired external process/ innovation facilitators	Has dedicated product developer employed	
	Project-wise developed new products in cooperation with, e.g. Henning Larsen architects			Closed contact to architects who has direct customer contact	
Case 4	10 % off all employees have main focus on NPD	Has a formalized innovation model, such as a stage-gate model	Has dedicated innovation committees in the organization	Has changed company focus from being a production company to be a customer-oriented company	Engineering heavy company with focus on NPD
	Leading company in terms of counter-flow units			Attempts to influence national codes and regulations	
Case 5	Product is highly influence by possible production process technologies	As a consequence of market decline the company has had strong cost cutting programmes	Sees construction networks as their opportunity to handle resistance against new products	Seeks demonstration projects as showcase of new products	Material science and nanotechnology is central
	Struggles to develop new products and gain market acceptance	International company with many alliances			

(continued)

Table 3 (continued)

Innovation scope	Product	Process	Organization	Market	Technology
Case 6	Continuous development of new façade system, single and sandwich elements	Strong focus on business models and innovation processes	Network-based business models	Extensive amount of business partners close to customer	Fibre composite structures
	Recently focus on staircases and balconies also	Developed own innovation stage-gate model	Has business network with multiple companies in the supply chain		Moves on to off shore market

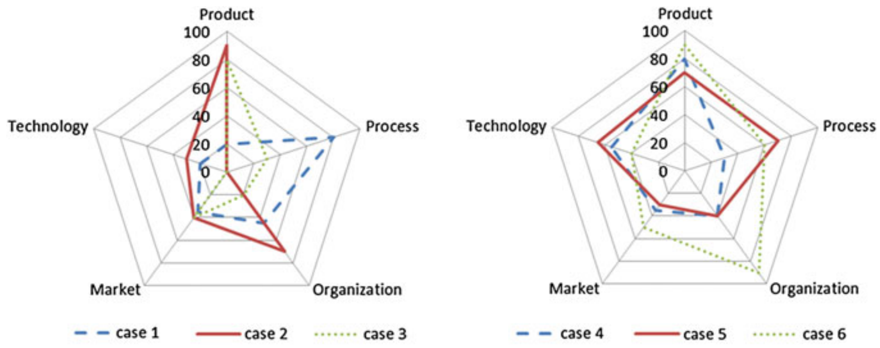

Fig. 1 Scopes of innovation in relation to each of the six cases

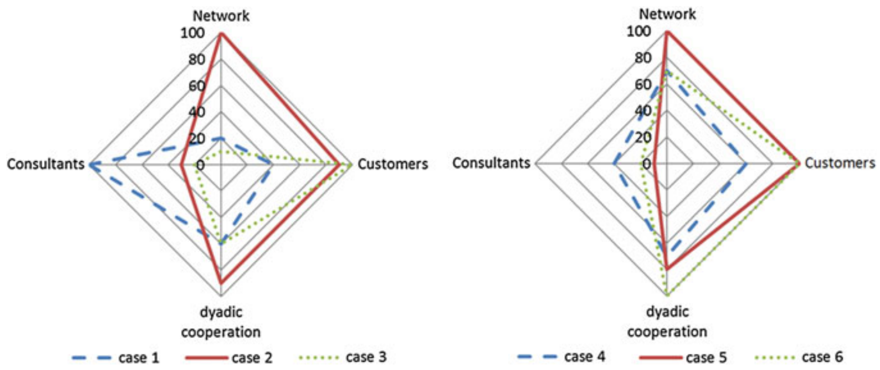

Fig. 2 External cooperation partners

user-focused design (case 2) over co-creation (case 3) to development of new business models (case 6).

The analysis also investigates who customers are. It is clear that the further upstream a company is in the value chain of construction, the less the company cooperates with partners close to the end-user. Cases 2 and 5 are most upstream and their customers are mainly the next tier of construction material producers. Cases 1, 3, 4, and 6 have a broader customer landscape and cooperate with mainly vendors but also with contractors and architects. In general, there seems to be a barrier in cooperation with traditional actors in construction projects. Hence, there is a risk that innovation only takes places with the next tier in the supply chain and leaves out the end customer of construction, i.e. clients and users. Architects are often involved in innovation with the construction material industry (cases 1, 2, 3, and 6) as a construction partner, whilst only cases 4 and 5 cooperate with contractors in innovation processes.

Dyadic cooperation is collaboration between the focal company and either a supplier, a competitor, a university, or another company. All cases apply such dyadic cooperation in a medium or high degree in their innovation effort. The analysis discovered that cases 1, 2, 4, and 6 have more than one dyadic cooperation relation in their innovation campaign. Finally, four of the six cases participate in innovation network activities, e.g. InnoByg.[2] Thus, it can be concluded that all cases work with open innovation, however, in different manners and extent. No correlation between company size, maturity, or degree of processing and how open they are could be determined. More research should be delegated to explore this specific topic.

3.3 Innovation Maturity

It became clear from the interviews that the six cases differ in how structured they go about the innovation process, ranging from ad hoc to structured and delegated. To investigate this further, the five levels of innovation maturity identified by Essmann and Du Preez [18] are applied. The five levels are presented as follows:

- Level 1: The organization is wholly consumed with day-to-day operations—maximizing short-term revenue and reducing cost. Individual attempts at being creative or "out-of-the- ordinary" are often dismissed. Innovative outputs are inconsistent and unpredictable.
- Level 2: The organization has identified the need to innovate. Innovation is clearly defined. A basic understanding has been established of the various factors that influence innovation. Innovative outputs are inconsistent, but traceable.
- Level 3: Innovation is supported and managed with appropriate practices, procedures, and tools. Individuals are encouraged to be innovative. Innovative outputs are consistent in nature and ensure sustained market share and positioning.
- Level 4: Practices, procedures, and tools for integrating innovation activities are used. A deep understanding has been established of the internal innovation model and its relation to business requirements. Innovative outputs are consistent, diverse, and a source of differentiation.
- Level 5: Innovation practices, procedures, and tools are institutional. Individuals are empowered to innovate. Synergy is achieved through the alignment of business and innovation strategy and the synchronization of activities. Innovative outputs provide sustained competitive advantage in existing and new markets.

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[2] InnoByg is the innovation network for energy efficient and sustainable construction. The Danish Agency for Science, Technology and Innovation has granted a co-financing of 20 million DKK to the new network in the period 2011–2014.

Based on interviews, observations and archives of each case are in one of the five levels for innovation maturity in organizations in the following.

Case 1 has delegated the responsibility for the innovation process to key employees. For example., the production manager was a blue collar employee a few years prior to this research. He is currently responsible for the continuous development (known as continuous development or Kaizen) of the production and is the team manager for the whole production. The hourly paid workers have an additionally pay based on incentives from production optimization ideas. Also, a product development manager in charge of LEAN innovation is employed. Top management seldom interferes in this process. Monthly employee meetings in the production are carried out. These facts correspond well with level 3, where innovation is somewhat supported and managed with appropriate practices, procedures, and tools. Case 1 is a medium-sized company with 140 employees and was founded in 1978.

Case 2 is placed in level 1 in terms of innovation maturity. In this level, the company applies all its energy on developing a product and to gain a market share. As mentioned, case 2 has high focus on product innovation and struggles to gain a relative market share. Essmann and Du Preez [18] argue that in this level, focus is put on short-term revenues and planning. During interviews, the CEO of case 2 only talked about the technical specifications and the profits that can be gained of his one product. Case 2 is a small company with only 11 employees and was founded in 1999.

Case 3 is in level 2. This phase is characterized by introduction of structures, systems, and procedures for directing the development process. The company has recently reorganized itself with more firm direction for product development. As a part of the reorganization, they developed an innovation laboratory where customers can come and "play" and assemble heating components.

Case 4 introduced a strong restructuring of their development activities 4 years ago. This structure contains procedures for prioritizing and selecting innovative ideas. The company was founded in 1957 and has today 175 employees. Therefore, case 4 is placed in level 4, which implies the use of practices, procedures, and tools for integrating innovation activities to enhance co-ordination.

Case 5 is placed in level 3. During this level, a company can have different development projects with separate (and conflicting) agendas. Each project has its own leader who only focuses on that particular project and fails to take the whole company into consideration in the decisions that are made. The Head of Development in case 5 is currently facing these challenges. He is in the process of developing new structures and procedures for the future innovation process of the organization. He also struggles to prioritize the different projects to ensure that the scarce organizational resources are spent efficiently. Case 5 is an old company founded in 1889 with 371 employees.

Case 6 is, similar to case 3, placed in level 2. It has just moved away from a "leadership crisis," due to a new CEO and his strategic efforts in the company. So, whilst the organization has identified the need to innovate and that innovation is clearly defined, little effort has been put into activities for conducting innovation

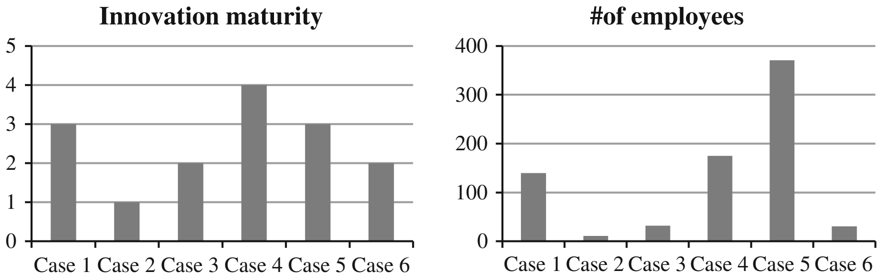

Fig. 3 Innovation maturity

due to the change in management. It is a small organization and has existed for merely 10 years.

As illustrated in Fig. 3, there is a pattern that the size of the organization has an influence on the level of innovation maturity. This is not a significant linear pattern, but does provide indications that innovation maturity in constructional material companies may in fact be dependent on the general organizational maturity.

4 Discussion

Despite the largely negative picture of innovation in the construction industry, some SMEs do manage to deliver innovations of significant originality [25]. The ways in which these successful innovators operate and how they differ from less innovative businesses are likely to provide useful illustrative examples. For this reason, a study focusing on enablers for innovation in SMEs in the construction industry can make a contribution to understanding how and why some firms are able to counter the trend set by many of their peers.

To discuss research findings from the six case studies and in the quest of generalizing factors that enables innovation, findings from a range of past studies on innovation in the construction industry are drawn upon.

Most of past studies have a broader scope than the construction material industry, instead focusing on the construction industry in general or the project-based condition of construction projects. The following enablers are the most dominant (often occurring) from litterateur in and around the construction industry.

4.1 Collaboration with External Partners

What we find throughout the analysis is that collaboration with the external environment is a key enabler of innovation in the construction material industry, and that this is often practiced with several different scopes of innovation. This finding is supported by several studies pinpointing that industry relationships, both up and down stream in the supply chain, have a significant impact on innovation [26, 27]. The benefit of strong relationships must be utilized through careful facilitation, which can enable knowledge flow and transactions [4]. This can include processes related to product integration, project organization and coordination, diffusion of technologies, and information flow from various sources [28]. For example., manufacturing firms are often considered a key source for construction innovation, because they often provide innovative components [4]. Anderson and Manseau [28] argue that manufacturing firms have larger R&D programmes due to their more stable boundary conditions. Moreover, their focus and production is not project based that prevents them from learning discontinuities.

Miozzo and Dewick [27] found that the strength of inter-organizational cooperation in the construction industry in five European countries is responsible for enhanced innovative performance. Stable relations, almost quasi-firm like, ensures mutual interest, active participation, and open communication. These elements, combined with continuing cooperation, is an enabler of both product and process innovation [27]. Synonyms for such a relationship could be relational contracting and strategic alliances.

Downstream, we also find that costumers with a technical insight are considered to have enormous capacity to exert influence on firms involved in construction in a way that fosters innovation [4, 29–32]. Customers are able to enhance innovation in construction in a number of ways. The more demanding and technically oriented the costumer is, the more likely it is to stimulate innovation [30, 32, 33]. Manley [34] has demonstrated that a high level of technical competence in the costumer body is a significant enabler for construction innovation. Nam and Tatum [29] have pointed out that customers' values are not necessarily as conservative as they are sometimes perceived to be. Some construction customers are able to accept and encourage innovation in the building projects that they commission [35].

Wandahl et al. [2] and Lassen et al. [36] argue a major challenge for companies working with innovation in the construction industry is the development of an understanding of the importance of working trans-disciplinary within the various companies in value chain. To innovate in an open innovation setting, the involved companies must overcome these challenges. That openness enables innovation is demonstrated in the analysis of the cases in this study, as well as in the work of Dubois and Gadde [26] who concluded that up and down stream relations had significant impact on innovation performance.

4.2 Trust

In close relation to cross-organizational tiers and communication, trust within such a collaborative establishment becomes crucial [37]. Akintoye and Main [38] found lack of trust to be one out of two major reasons for not succeeding with innovation in construction. Bosch-Sijtsema and Postma [39] argues that mutual trust amongst partners can lead to access to and further development of the knowledge and innovation.

Akintoye and Main [38] identify success and failure factors for collaboration in the construction industry in the UK. One of two principle failure factors is defined as being lack of trust and consultation amongst the business partners.

Bosch-Sijtsema and Postma [39] claim that: "partnerships with complimentary technological capabilities and mutual trust relationships develop and share (new) knowledge on organizational and market issues…can be positive for the innovation potential and for developing and strengthening competitive advantage" (p. 69). Thus, mutual trust amongst the business network partners in the construction industry can lead to further development of the knowledge and innovation of all business network partners, which in return support the general industrial relationships.

Jacobsen and Lassen [37] have also stressed the importance of trust between collaborative partners in the construction industry. They state that, generally, the element of trust is a well-known and researched field; however, it proved to be an absolutely essential element in the construction industry due to the general industry inexperience in collaborating for innovation. They state that different kinds of trust exist during a trust development process for an innovation project in the construction industry, and that these types of trust are developed through certain activities which ensure success of the collaboration.

The element of trust may in fact be related to the innovation maturity of the organization, as it takes time to develop relationships, procedures, and structures that enable innovation.

4.3 Management Support

The available resources of a firm are widely regarded as critical for innovation success. The case analysis reveals that "trial and error" nature of much innovation requires a supportive management structure and sufficient resource allocation if it is to deliver benefits [35]. The organizational structure and awareness from top management seems critical [2, 40]. Also the competences of top and middle management have proven impact on innovation [41]. Ownership of the innovation process is important both when a single firm innovates and in inter-firm innovation. A dedicate resource that facilitates and drives the process must be present. Slaughter [42] mentions the role of "gatekeepers," whilst Mitropoulos and Tatum [43] and Gambatese and Hallowell [41] identify this role as "champions." The role of the champion is close to the concept of the innovation broker [4, 10, 44].

Bosch-Sijtsema and Postma [39] state that one of the main conditions for accomplishing a collaborative innovation project in the construction industry is the top management support of the individual business partners: "*Especially* *managerial support increases the opportunity of transferring knowledge and internalizing this knowledge in the firm,*" which supports the ability of creating, enhancing, and facilitating the innovation skills of the business network.

Another aspect that must be considered is that often in the construction industry, it is in fact the top management that comes up with the innovation [29]. As such, top management support to, and sometimes direct involvement in, the collaboration for innovation in the construction industry becomes a necessity for developing and cultivating innovation. Management support can also be applied through trust to the individual departments and hereby allowing a certain degree of freedom to explore potential innovative directions.

However, considering the traditional and norm-bound setting of the construction industry, ensuring success of collaboration for innovation requires further education and re-orientation of the construction industry in general [45].

A key observation made by Wandahl et al. [2] and Jacobsen and Lassen [37] is that innovation managers in the construction industry have very different degrees of freedom to act within. For cross-organizational collaboration, these differences in mandate turned out to be a hurdle in an open innovation process. Nam and Tatum [29] illustrate that top management often is the main the driver of innovative ideas in construction. Thus, it is evident that organizational structure and awareness from top management is a critical enabler for innovation in the construction material industry [2, 35, 40].

5 Conclusion

In conclusion, focus returns to the research question which is set forth in this research, focusing on how innovative processes is structured and managed in successful construction material firms. In other words, identifying, describing, and discussing the innovation enablers in construction supply chains.

Through this paper it has been discussed how different structures and innovative practices in general, in a fuzzy compound can set the foundation for successful innovation in construction material firms. These practices are to be viewed in a larger scope of transforming the whole construction industry into a more innovative industry. Boundary conditions, however, calls for an open or network-based approach to innovation in the construction industry.

The result of this research is knowledge of the practices, which support innovation within construction material firms. A range of practices that can lead to successful innovation has been discovered, some through literature and some through analysis of empirical data. The main point to observe is that successful innovative firms apply a combination of different innovative actions simultaneously. Such companies are open-minded and pursue innovation in multiple directions, e.g. technological, organizational, etc. It is, therefore, not possible to put forward a recipe-like agenda on how to be innovative as this is highly depended on the given context and the capacities within the firm. It is, however, possible to point out precepts for increased success ratio.

Peer research has proven that management support, organizational structure, firm resources, and selection of champions are innovation enablers. This research documents an additional enabler—that initiating innovation processes from multiple sources simultaneously seems to enable innovative success. This is important to incorporate as rigid structures of innovation practices emerges as companies matures.

All cases in this research practice dyadic collaboration and open innovation, which therefore seems to be an enabler. More precise, it is recognized that open or network-based innovation within the supply chain (i.e. with suppliers and customers) as well as innovation processes outside the supply chain with industrial partners or even competitors increases the chance of successful innovation for construction material firms.

Whether or not the innovative actions are conducted internally or externally, trust is paramount to establish due to the fragile culture of collaboration. This research enclosed that ownership to the innovation process is critical especially in a network-based approach.

A final enabler verified through this research is that successful firms actively try to influence the regulatory climate to achieve a competitive advantage.

This research has identified the abovementioned precepts for innovative practice within the construction material industry. Theses precepts should be explored in greater detail in future research to investigate and describe the constraints in greater detail.

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Enabling Facilitation of Mass Customization via Partnering in the Construction Industry

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Abstract In the past decades, the manufacturing industry has gone through dramatic improvement in productivity, cycle time, and inventory level of manufacturing applying information technology and manufacturing technology. However, the construction industry has not yet been able to enjoy similar magnitude of improvements. The aim of this paper is therefore to investigate which of the normally used procurement forms in the Danish construction industry would facilitate the implementing mass customization. Benchmark results from 2,318 cases were obtained from The Benchmark Centre for the Danish Construction Sector containing information on the realization processes and the integration of customers likely to answer the question of which procurement or contract form that would best accommodate the facilitation of near-mass customization performance. To test this, a one-way ANOVA comparison was used, and it was found that Partnering and Turnkey Contracts significantly enhance the likelihood of facilitating the implementing mass customization than all other contract forms.

Keywords Partnering · Mass customization · Construction · Statistics

1 Introduction

In the new era of competitive environment, customer demands for high variety of product choices [16]. At the same moment, customers increasingly show an interest of self-customization of the item to personalize the product [5]. Manufacturers such as construction companies understand that customers are the driver of the market, in order to accommodate the needs of customer; they are attempting

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to produce a large number of product variants in an economical way. Mass customization philosophy seems to show a possibility to help construction companies to achieve this goal by achieving mass production efficient in an economic way while allowing customizing at the same moment [15]. However, to apply mass customization successfully on an industry such as the construction industry, an effective and efficient customer requirement collecting and implementing platform, high-performance manufacturing processes, and well-maintained supply chain support are required. To facilitate functions of these enablers, a contracting model that facilitates the implementing mass customization is necessary.

Modern building system is closely bonded with the development and the substantiality of the society [20]. The construction process in the future should allow flexibility to perform modification uttered from the customers and keep pace with the changes along the changing world in terms of technology and development [20]. Even though the construction process is inseparable with our breath, construction industry is still sticking to the traditional way of practice in terms of project management and production strategy. In terms of business process, the constructing a building is a very complex process; it involves numerous stages of iterations and collaboration between government, construction professionals, and developers; different disciplines each with their own interests and mastery area.

The mass customization movement has evolved a lot over the past years [12]. Once publically recognized merely as a new way to sell consumer goods such as customized cereal or running shoes, these days' mass customization has gained acceptance and application as a revolutionary way to design, make and sell the products of the future, and to help form a better, more individual society for individual people [12].

One such area where the concept of mass customization is currently winning more and more fans is that of architecture and building construction. Why?!—Because no two inhabitants are exactly the same and the house one lives in should reflect that. More so, since it is not only a rather expensive product but a home, a place where one should feel completely comfortable. Research has shown that mass customization can help to make the dream of the truly individual house an affordable reality (within certain limits, of course) [23]. However, the concept has far more potential than what is being put to use these days. When analyzing architecture and the construction industry with regard to the strategic capabilities of mass customization that have been suggested by literature, opportunities for improvement, especially in terms of the realization processes and the integration of customers, can be recognized [12].

Mass customization can be described as "enabling a customer to decide the exact specification of a product or service, and have that product or service supplied to them at a price close to that for an ordinary mass-produced alternative" [10]. The first part of this definition, the "involvement of the customer in deciding the exact specification" means that the relationship between the vendor and the customer is different to a mass production situation, where the vendor offers a product on a "take it or leave it" basis. In a study entitled "Approaches to mass customization: Configurations and empirical validation" Rebecca Duray et al. [7] states that mass customization takes place when a product is designed to meet the needs of a particular customer. Whereas increased product variety is sometimes cited to support descriptions of mass customization, here it is argued that the customer must be involved in specifying the product for true mass customization to take place [7]. This type of mass customization is sometimes known as "collaborative customization," a term which was coined in a 1997 Harvard Business Review article "The Four Faces of Mass Customization" by B. Joseph Pine and James H. Gilmore [10]. Collaborative customization is where the business conducts a dialog with the individual customer to help them articulate their needs, to identify the precise offering that fulfills those needs, and to make customized products for them. This approach is appropriate for businesses whose customers cannot easily articulate what they want and grow frustrated when forced to select from a plethora of options. This involvement of the customer in the design and production stage means that the customer becomes a "prosumer" as described by futurologist Alvin Toffler in the 1970 book, "Future Shock" [22]. The prosumer is producer and consumer in concert, defining and producing the product. The second part of the definition refers to the price, which must be "close to that for an ordinary mass-produced alternative". This addresses the "mass" in mass customization. This separates mass customization from the traditional "made to order" approach, which by nature involves high cost, for example, in construction of complex buildings. At the extreme of mass and collaborative customization is "pure customization" as described by Henry Mintzberg in 1988 [19]. This is where an enterprise supplies a product designed and produced from scratch for each individual customer. Pure customization includes the customer in the entire cycle, from design through fabrication, assembly, and delivery, and it provides a highly customized product.

The aim of this paper is therefore to investigate which of the normally used procurement forms in the Danish construction industry would facilitate the implementing mass customization. This is based on the argument that the customer must be involved in specifying the product for true mass customization to take place, since analysis of architecture and the construction industry with regard to the strategic capabilities of mass customization have been suggesting opportunities for improvement, especially in terms of the realization processes and the integration of customers for near-mass customization performance outlet.

2 Methodology

When doing so, i.e., arguing which procurement form that would best facilitate mass customization performance outlet, facilitate is defined as rendering probability and/or substantiate the use of mass customization philosophy in a construction process. Best indicates the one with highest likelihood for facilitating mass customization of the normally used procurement forms not implying that other forms of procurement under certain conditions could not be at least as preferable.

Procurement implies both the dedicated processes where tenders are invited to bid on a project and the process following where different collaboration forms are used to undertake the construction; different procurement forms yield different collaboration form per say, traditional procurement normally calls for traditional ways of collaborating where procurement forms such as partnering enforces the use of value-based collaboration, not taking special cases into account. As mentioned before, "best" indicates the one form with highest likelihood of facilitating mass customization, the selected indicators or variables of this is as follows: The contractors' ability to:

1. Aid constructively with project analysis or with planning of the project before the on-site contract start
2. Find solutions in accordance with the demands in the specifications and also to accommodate the client's needs and wishes within the agreed contract framework/term
3. Meet time schedules and hand over the contract on time
4. Enter dialog regarding additional works and pricing of these
5. Participate in a constructive dialog and contribute to a good working relationship between the projects key personnel
6. Be considerate to the construction sites vicinity, e.g., neighbors, tenants, other personnel, and any users of the building under construction
7. Contribute toward completing a satisfactory handing over
8. Deliver information regarding facility management in accordance with the demands in the specifications.

This is all summed into a dependent variable called customer satisfaction (CS) given the definition that mass customization takes place when a product which is designed to meet the needs of a particular customer [21] and where the contractor conducts a dialog with the individual customer to help them articulate their needs, to identify the precise offering that fulfills those needs, and to make customized products for them [13]. To test how different procurement and collaboration methods affect the CS procurement form is selected as a test factor.

To sum up, the dependent measure is the CS, and the factor affecting it is the procurement method. To test the hypotheses that: (1) Partnering results in better marks in CS than either of the traditional procurement methods; and (2) that Turnkey Contracts is the second best alternative to Partnering Contracts; a one-way ANOVA statistical tests were carried out using SPSS.

3 Results

To test how different procurement and Contract forms affected the dependent variable called CS data on the contractor's ability to aid constructively with project analysis or with planning of the project before the on-site contract start; to find

Table 1 Descriptive statistics form the one-way ANOVA, SPSS

		N	Mean	Std. deviation	Std. error	95 % Confidence interval for mean	
						Lower bound	Upper bound
Trade Contracts		22	3.2690	0.27289	0.05818	3.1480	3.3900
Major Contracts		22	3.5805	0.13278	0.02831	3.5216	3.6393
Main Contracts		22	3.6035	0.19461	0.04149	3.5232	3.6958
Turnkey Contract		22	3.6530	0.27800	0.05927	3.5298	3.7763
Partnering Contract		22	3.7296	0.40875	0.08715	3.5484	3.9109
Total		110	3.5683	0.31189	0.02974	3.5094	3.6273
Model	Fixed effects			0.27362	0.02609	3.5166	3.6201
	Random effects				0.07894	3.3491	3.7875

Customer satisfaction with the construction process

Table 2 Test of the assumption of homogeneity of variance (Levene's test), SPSS

Levene statistic	df1	df2	Sig.
14.845	4	105	0.136

Customer satisfaction with the construction process

solutions in accordance with the demands in the specifications and also to accommodate the client's needs and wishes within the agreed contract framework/term; ability to meet time schedules and hand over the contract on time; to enter dialog regarding additional works and pricing of these; to participate in a constructive dialog and contribute to a good working relationship between the projects key personnel; to be considerate to the construction sites vicinity, e.g., neighbors, tenants, other personnel and any users of the building under construction; to contribute toward completing a satisfactory handing over, and to deliver information regarding facility management in accordance with the demands in the specifications was obtained from The Benchmark Centre for the Danish Construction Sector containing benchmark results from 2,318 cases.

The test comprises of a one-way ANOVA and uses planned comparisons to test the hypotheses that: (1) Partnering results in better marks in CS than either of the traditional procurement methods; and (2) that Turnkey Contracts is the second best alternative to Partnering Contracts when it comes to enabling facilitation of mass customization based on aforementioned premises.

Table 1 shows the table of descriptive statistics from the one-way ANOVA; it shows the means, standard deviations, and standard errors of the means for each experimental condition. These diagnostics are important for interpretation later on.

Table 3 Main ANOVA summary table, SPSS

			Sum of squares	df	Mean square	F	Sig.
Between groups	(combined)		2.742	4	0.686	9.156	0.000
	Linear term	Contrast	0.062	1	0.062	0.826	0.365
		Deviation	2.680	3	0.893	11.933	0.000
Within groups			7.861	105	0.075		
Total			10.603	109			

Customer satisfaction with the construction process

Table 4 Contrast coefficients used to test hypotheses, SPSS

Contrast	Procurement form				
	Main Contracts	Turnkey Contract	Trade Contracts	Major Contracts	Partnering Contract
1	1	1	1	1	−4
2	1	−3	1	1	0

Table 5 Results of contrast coefficients test, SPSS

Contrast			Value of contrast	Std. error	t	df	Sig.(2-tailed)
Customer satisfaction with the construction process	Assume equal variances	1	−0.8065	0.26088	−3.091	105	0.003
		2	−0.5002	0.20208	−2.475	105	0.015
	Does not assume equal variances	1	−0.8065	0.36184	−2.229	24.3	0.035
		2	−0.5002	0.19371	−2.582	29.1	0.015

It looks as though CS is highest when the procurement form Partnering Contract (3.7296) is used and lowest when using Trade Contracts (3.2690).

The next part of the output (Table 2) reports a test of the assumption of homogeneity of variance (Levene's test). For these data, the assumption of homogeneity of variance has been met, because our significance is 0.095, which is larger than the criterion of 0.05.

Table 3 is the main ANOVA summary table; it shows us that because the observed significance value is less than 0.05, we can say that there was a significant effect of selected procurement form on CS. However, at this stage, we still do not know exactly what the effect of the procurement form was (we do not know which groups differed).

Because there were specific hypotheses, some contrast needs to be specified. Table 4 shows the codes used. The first contrast compares Partnering Contract (coded with −4) against all the other procurement forms (all coded with 1). The second contrast compares Turnkey Contract (coded with −3) against all other (coded with 1). Note that the codes for each contrast sum to zero and that in contrast 2, Partnering Contract has been coded with a 0 because it is excluded from that contrast.

Table 5 shows the significance of the two contrasts specified above. Because homogeneity of variance was met, this means that the part of the table labeled; Does not assume equal variances can be ignored. The *t*-test for the first contrast tells us that Partnering Contract was significantly different from the other Contract forms (it is significantly different because the value in the column labeled Sig. is less than 0.05). Looking at the means, this tells that the average CS using Partnering Contract was significantly higher (3.7296) than the average CS for all the other Contract forms combined (3.528). The second contrast (together with the descriptive statistics) tells that the CS after Main, Major, and Trade Contracts were significantly lower than after Turnkey Contracts (again, significantly different because the value in the column labeled Sig. is less than 0.05). As such it can be concluded that Partnering Contracts produces significantly better CS than all other Contract forms, and Main, Major, and Trade Contracts produces significantly worse CS than Turnkey Contracts.

3.1 Calculating the Effect Size

Table 3 provides three measures of variance: the between-group effect (SSM), the within-subject effect (MSR), and the total amount of variance in the data (SST). This can be used to calculate omega squared (ω^2):

$$\omega^2 = \frac{SS_M - (df_M)MS_R}{SS_T + MS_R}$$

Substituting from output in Table 3:

$$\omega^2 = \frac{2.742 - (4)0.075}{10.603 + 0.075}$$

$$\omega^2 = 0.2287$$

$$\omega = 0.48$$

For the contrasts, the effect sizes will be:

$$r_{\text{contrast}} = \sqrt{\frac{t^2}{t^2 + df}}$$

The result for contrasts 1 and 2 is as follows:

$$r_{\text{contrast},1} = \sqrt{\frac{(-3.091)^2}{(-3.091)^2 + 44}} = 0.18 \quad \text{and}$$

$$r_{\text{contrast},2} = \sqrt{\frac{(-2.475)^2}{(-2.475)^2 + 44}} = 0.12$$

Therefore, as well as being statistically significant, this effect is medium, and so represents a substantive finding. This too is a substantive finding and represents a small to medium effect size. All significant values are reported at $p < 0.05$. There was a significant effect of procurement (Contract) form on CS, $F(4, 44) = 9.2$, $\omega^2 = 0.48$. Planned contrasts revealed that Partnering Contracts produced significantly better CS than all other Contract forms, $t(44) = -3.1$, $r = 0.18$, and that Main, Major, and Trade Contracts produced significantly CS than Turnkey Contracts (Partnering held aside), $t(44) = -2.5$, $r = 0.12$.

4 Discussion

So why this focus on selecting the right procurement or contract form, because studies have shown, including this, that different contracting form yield different outcomes and different processes under which the consumers' demands are met. When using Partnering or Turnkey Contracts, numerous advantages and inducements are highlighted in the literature (e.g., minimization of costs, bidding prices and waste; increased efficiency and effectiveness; increased innovation; better quality [6, 17, 18]; better design; better sharing of project risks [14]; better use of labor; improved communication; reduction in conflicts, claims, and disputes [9, 11, 17, 18]; higher level of supply chain collaboration [2, 4], and more information in the decision-making [1]. Also [8] described partnering as a way to avoid conflicts, minimize costs, reduce time, and yield a better working environment. The possible cost savings ranged from 5 to 30 %, and possible time savings ranged from 10 to 40 % [6, 8].

Furthermore, besides the included key factors contained in partnering, it also uses a clearly defined risk allocation with gain share/pain share to manage the process. In this model, parties contractually commit to their contribution levels and required profit and then place these at risk in undertaking the project. This provides a powerful incentive to achieve project goals [3].

To answer the why, the step-forward in the construction industry is to deliver added value, as expressed by the consumer, not only in terms of end product, but of process as well. An open consumer-oriented building process does not mean that an infinite number of options have to be offered. In a tailor-made house, the single desired option is enough. An infinite offer of variety is the other extreme of consumer satisfaction. In a process of mass customization, a limited number of options can be sufficient. This is a strategic decision, which will differ from company, market segment, location and time. In all cases, it is important to keep the customer satisfied. He wants to know the selection to choose from and how to choose and since every option is measured against the available budget, the consumer wants to know the cost implication of every combination of options.

5 Conclusion

The aim of this paper was to investigate which of the normally used procurement or contracts forms in the Danish construction industry would facilitate the implementing mass customization, based on the argument that the customer must be involved in specifying the product for true mass customization to take place and in terms of the realization processes and the integration of customers for near-mass customization performance outlet. So, to apply mass customization successfully on an industry such as the construction industry, an effective and efficient customer requirement collecting and implementing platform, high-performance manufacturing processes, and well-maintained supply chain support are required. To facilitate functions of these enablers, a contracting model that facilitates the implementing mass customization is necessary. In this study, there is here found strong indicators pointing out that to succeed implementing near-mass customization in the construction industry the best choice would be Partnering or Turnkey Contracts because Partnering and Turnkey Contract differed significantly from the other contract forms in case of average CS, where Partnering Contract was rated higher (3.7296) and Turnkey (3.6530) than the average CS for all the other contract forms combined (3.528). Looking at homogeneity of variance, contrasts and t tests, all showed great significance, as such it can be conclude that Partnering Contracts produces significantly better CS than all other contract forms, and Main, Major, and Trade Contracts produces significantly worse CS than Turnkey Contracts, thus improving the likelihood of best facilitating the implementing mass customization in the construction industry

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Extending Configuration and Validation of Customized Products by Implicit Features in Virtual Reality Environments

Angel Bachvarov, Stoyan Maleshkov and Dimo Chotrov

Abstract The virtual reality (VR) is an environment, which enables the proactive participation of the customers in defining their needs and requirements within the product development process. However, the traditional approaches for representation of physically existing objects (products) using VR show only a few of their properties (geometric, structural, and topological). The potential of VR as technology for efficient validation of still not-materialized artifacts in the early design stages is not fully exploited. In order to improve the immersion and to enable customers in configuring more aspects of the newly created customized products, as well as to validate these through "experiencing," we propose the concept of so-called implicit features representing "hidden" product properties (i.e., magnetization, surface roughness, and humidity), which normally are not part of the object model, cannot be perceived directly, and are not exposed for configuration. Here, we discuss the implicit feature concept, their implementation, and their use for customer co-design.

Keywords Virtual reality · Implicit features · Configuration · Validation · Customer co-design · Customized product

1 Introduction

A process in which the customer selects different attributes and attribute values from a finite set of options and combines them into a final individualized product is known as product configuration process. In the product configuration, the

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costumers act as co-designers of the new product. Actually, it is a two-way continuous exploration and interaction between the product (its respective producer) and the customers in which the customer needs are identified, processed, prioritised, and translated in engineering requirements on which base the customized product shall be materialized. Beside that, a validation of the generated product configuration can be made before its materialization.

The virtual reality (VR) provides an environment, which enables the proactive participation of the customers in defining their needs and requirements and interactive multimodal validation of the properties of the configured products in the early stages of their development. Using VR technologies, the customers are allowed to carry out more efficient mapping of their functional requirements into the physical domain, and then, they are able not only to observe or simulate the individual creation, but also to "experience" it through multiple sensorial channels, e.g., visual, audible, and tactile. The primary source for the representation of the virtual object (VO) properties in the virtual environment is a combination of multiple presentational elements corresponding to the individual modalities used in the VR system. This is especially useful and efficient in cases of complex engineering products when multiple decisions have to be taken related to various aspects of the product.

2 Brief Explanation of Virtual Objects

The VOs, hereafter referred to only as "objects," are elements that make up the virtual environment and represent the real existing (materialized) objects, e.g., products. They play the role of an interface through which the users receive the virtual experience and the perception of presence as shown in Fig. 1.

According to the formalization presented in [1], the VO can be observed as an artifact resulting from human activity, which has an extension in the physical domain and creates a sense of presence. The VO is defined as follows:

$$\mathrm{VO} = \{\mathrm{E}, \mathrm{MC}, \mathrm{VP}, \mathrm{PP}, \mathrm{FR}, \mathrm{ES}\}$$

where

E is the sum of its constituent elements
MC is a plurality of morphological characteristics
VP is the set of visual properties
PP is the set of physical properties
FR is the set of functional relationships
ES is the state of being.

However, this is a rather complicated and practically unusable scheme description. A more practical representation that allows definition of VOs properties is proposed by [2]. According to it, VOs similar to the physical ones are

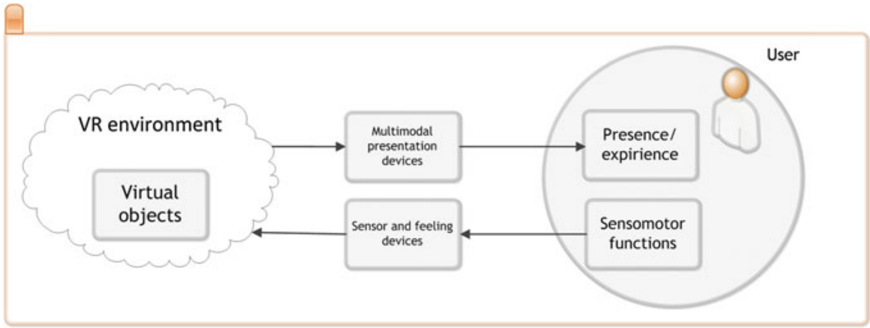

Fig. 1 VOs as part of the VR system

characterized by three main aspects that determine the specifics of the process of their creation: (1) *shape*, (2) *function* and (3) *behavior*.

Here, **Shape** refers to the "appearance" of the VO and its geometric properties as well as to the spatial relations between its constituent elements describing the object's structure (topology). Usually, the "appearance" is associated with visual sensory channel, but part of it may be associated with other senses: hearing, tactile sense, etc. **Function** refers to a set of elementary actions that the VO executes autonomously or in response to an external stimulus to realize its behavior. **Behavior** refers to the way in which the individual VO changes dynamically and performs its separate functions, usually presented in terms of conditions, data exchange, events, and internal restrictions. The behavior and functions are similar in nature, but their separation is necessary for the easy definition of dynamic objects.

In accordance with one of its definitions [3], VR can be observed as a high-end *user interface* of a specialized computer system that allows the user to "immerse" and "experience" interactively real-time simulation of VOs in an artificial environment using all his sensory channels. The basic paradigm used today in the design of advanced user interfaces [4, 5] considers the communication with the user as a transfer of messages (at semantic level) or presentation elements (at physical level). In this context, the creation of VOs can be seen as a multimodal combination of various presentation elements carrying information, which produces a picture in the user's mind of the VO's nature and properties.

Figure 2a, b shows a comparison between a real (i.e., materialized) and a VO. In case of a real object (Fig. 2a), the source of the process of forming the object picture is performed by the real physically existing object itself [4]. Such an object may be influenced by its environment in various ways, e.g., through filling a part of the physical space, causing changes in the surrounding objects, and releasing of substances. These effects of the real objects are registered by the user's sensory organs, then are transformed in perceptions, and at the end are interpreted as a mental picture of the object. In case of a VO (Fig. 2b), the primary source of information for the nature and properties of the object is not the VO itself but the

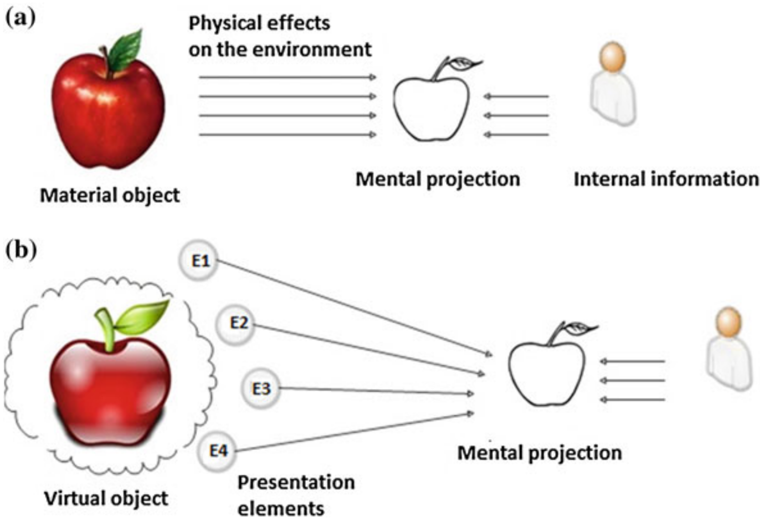

Fig. 2 Comparison between **a** material and **b** VO

combination of several different presentation elements. Each of these presentation elements is produced individually, and all of them are activated simultaneously as a result of the user actions.

3 Representation of Object Properties in VR Environments

In general, the VO model is a description thereof in the form of a special data structure. Depending on its type, it can contain information about the geometry, the structure (topology), the behavior, etc. When used in VR systems, these data have to be processed and produced a virtual representation through synthetic "sensory images" of all the objects and their spatial and temporal organization in the virtual environment. The creation of the sensory images of the individual objects can be divided into two phases: (1) *representation* and (2) *implementation*.

In the representation phase, a choice is made how the VOs will look, sound, and be felt by the user. In the implementation phase, the selected representation method is implemented through a hardware and software system for VR presentation. The choice of an appropriate form of presentation is highly dependent on the purpose of the respective application and the nature of the properties, which have to be presented in the virtual environment. In certain cases, when presenting quantitative information, the user needs to retrieve numeric values based on the perceived sensory image. This can be done directly (by numerical tables) or indirectly (through a variety of methods for displaying data in the different sensory channels). In other cases, the information to be presented is of qualitative nature or requires combination of quantitative and qualitative data produced in form of signs and symbols that require additional interpretation by the user.

Summarizing research work in this field as in [2, 5–9], a general practical approach for managing properties of VOs in virtual environments has been developed. The approach includes the following four steps: (1) Choosing the property to be presented, (2) choosing the parameters of the virtual environment, which will transmit the information about the presented property, (3) mapping the properties to be presented to the selected parameter, and (4) implementation in the virtual environment.

4 Implicit Properties

The term implicit property or implicit feature is not unknown. In the methodology of Kansei Engineering, it is used to describe the emotional experiences and needs of the customers, which are difficult to be quantified. Further, in the computer science, the implicit object features are the features of each object, which are not pre-computed/evaluated in case of information search [10]. We use the meaning of implicit features in completely different and new context. We propose an extension of the classification of the standardized properties of the material and VOs considering the way in which they can be perceived by the observer—perceived directly or "hidden." According to this, the object properties are divided in two major groups:

1. *Explicit properties*: These are the properties of the objects that can be perceived immediately by the observer through his/her senses (e.g., shape, color, and size).
2. *Implicit properties*: These are the properties of the objects that cannot be perceived by the observer through his/her senses (remain hidden), e.g., fields, radiation, humidity, and toxicity. They require expansion of the observer's sensory range.

The traditional approach for presentation of objects in VR environment is mainly based on their visual attributes (e.g., color, type, texture, and thickness of the lines). An example for this is shown in Fig. 3 for a hairdryer. The user can perceive its shape, color, topology, dimensions, and assembly structure. Normally, he can explore and interact with the VO trough a set of commands or gestures, which change its spatial position, size, and attribute values. The new approach aims at extending the information content and deepening the immersive representation of the object model in a VR environment through their enhancement with a predefined set of the above-explained implicit features.

An example for this is shown in Fig. 4. Here, beside the visually perceived attributes the user can get additional information concerning the functional

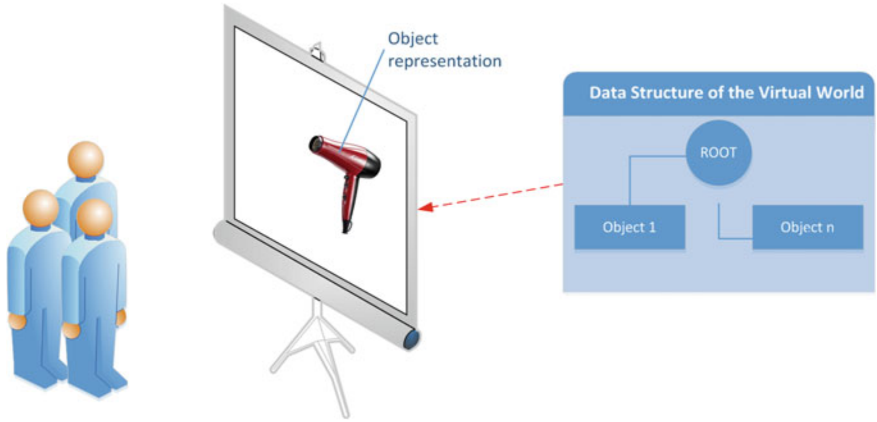

Fig. 3 Traditional object representation in virtual environment

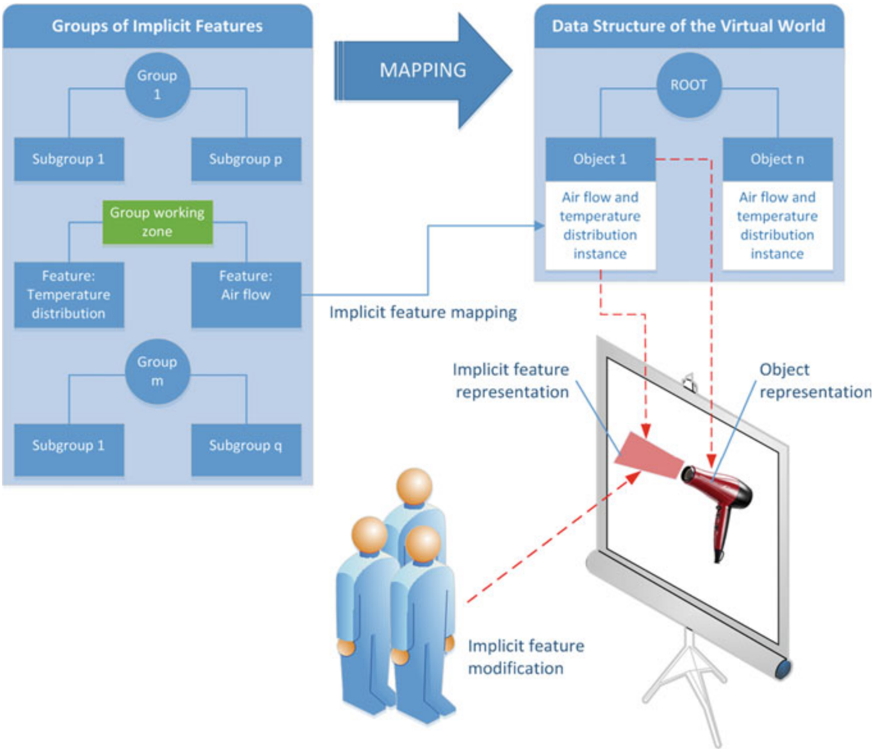

Fig. 4 Mapping implicit features to the VO geometry

behavior of the object. In this case, for example, he/she is able to explore and/or configure how the different combination of the hairdryer switches controlling the fan speed and heat output can influence the operating range. Further, the user can define the working area, which gives him/her an immediate idea for the safe way of use of the appliance. In this case, the operating range depends on the temperature and airflow distribution at the front of the appliance and could be observed as a complex implicit feature of the hairdryer. Depending on the needs, the properties can be presented only visually or in combination with sonification (by using sounds and noises to bring out information). Further, additional technical information related to the hairdryer operation can be presented such as the distribution of the housing surface temperature or noise emission (sound with respective characteristics) under different working conditions and modes.

From the point of view of the VR software system architecture, the implicit features are classified and described in a separate data structure independent from the programming application in use for building-up the geometry and for interaction in the VR environment. The mapping of the features to the scene geometry, attributes, and different sensory channels is carried out during the representation of the objects in the virtual world and provides the possibility to manipulate and modify the features as well as the related geometry directly in the virtual environment as shown in Fig. 4.

5 Practical Implementation of Implicit Features

Two different approaches have been developed and implemented for the representation of implicit object features in VR environments: (a) creating a dedicated software module as part of our in-house developed VR system and (b) extending the functionality of a commercially available VR software package.

The first method described in details below includes several additional components to our VR software system architecture built on the top of the SceniX scene graph software development kit designed by NVIDIA, which aims at representing virtual scenes interactively in high quality, taking advantage of the latest improvements in graphics hardware.

The second technique for implementing implicit features takes advantage of the functionality of commercial VR programming packages (in our research, we use Virtools) and applies build-in instruments for describing attributes and behavior of the VOs. In order to prepare a virtual model with implicit feature presentation for exploration in a VR environment, the user has to follow a number of steps as shown in the activity diagram in Fig. 5.

In the first place, the virtual model has to be designed in a digital content creation (DCC) or computer-aided design (CAD) application, for example, 3D Studio Max or SolidWorks. When the model is ready, it has to be exported to an appropriate file format supported by the VR application (i.e., 3DS, VRML, COLLADA, and OBJ). The assignment (mapping) of implicit features to the

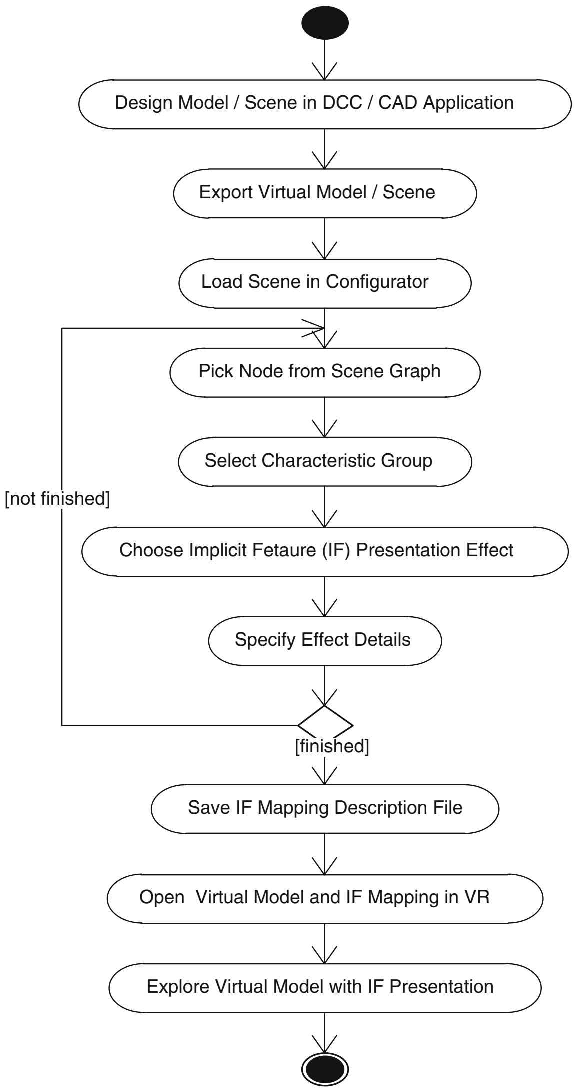

Fig. 5 Setting implicit features for a virtual scene

model follows. For the purpose, a special configuration application **(Configurator)** has been developed, which provides the user with the ability to import a model and assign implicit features to it—this process is called implicit feature mapping. The implicit features exposed by an object are represented by effects—one effect for each implicit feature. Effects are used to describe how an implicit feature is to be presented to the user by applying different sensorial stimuli. We concentrate on three types of sensorial stimulation—visual, audio, and haptic. Each effect provides different settings that can be modified by the user—for example, there are

Fig. 6 Hardware configurations for implementation of implicit features exploration in VR environment: single desktop system (*left*) and cluster system with powerwall (*right*)

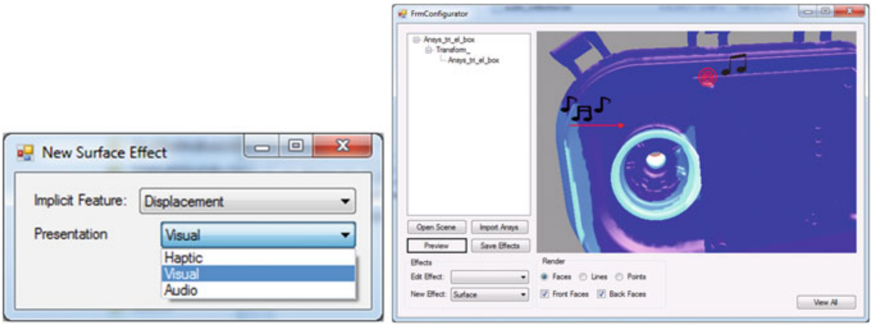

Fig. 7 An example for setting up a presentation effect for a selected implicit property within the implicit feature configurator

two types of audio effects—constant effects that are played continuously and effects that are played only during the period of time when the user interacts with the object in some way. After the implicit feature mapping process is finished, the configurator generates an implicit feature mapping description file, which describes the effects assigned to each of the objects features.

To explore and/or modify the built scene in a VR environment, the user activates the VR application. Two types of hardware configurations can be implemented: The application can run on a desktop machine or mobile device or a powerwall or cluster configuration can be realized as shown in Fig. 6.

The hardware configuration to be used together with additional settings is specified in a configuration file read by the application when it starts. After the user loads the virtual scene and the description file, he/she can explore the selected model/scene in VR environment.

The process of mapping two different presentation elements (visual, audible, and tactile) in order to present various object features simultaneously within a validation step can be observed in Fig. 7. The figure shows a virtual model of an electronic appliance case extended with additional implicit features (in this case information about surface roughness of the individual areas of the case which is extremely important for the production). Using the extended information, an audible presentation element is configured to present the different surface qualities. The assignment of presentation elements to the individual object properties is made using the configurator application upon selecting the respective VO from the scene tree. As a result, the user (customer) receives multimodal real-time feedback for selected implicit feature or features of the VO, which enables him/her to validate in terms to compare his initial requirements with the estimated functional properties of the newly created product configuration or to modify it further.

6 Conclusion

In this paper, we introduce the concept of implicit object features and propose their presentation in VR environments through mapping on different sensor channel modalities in order to extend the configuration and validation capabilities within early stages of the product development process enabling more active and efficient participation of the customer. Two directions for implementation of this approach have been followed: (1) development of a dedicated software module as part of our in-house developed VR system and (2) extending the functionality of commercially available VR software packages. This work can be considered a major step in transforming the VR technology from its current state of being only a high-end presentation show case toward an important tool for exploration and validation of design features contributing to the process of front-loading for reducing design cycles and "materialization time" of highly customized products with direct active involvement of the customers. Combining visual, auditory, and tactile sensory channels possesses a potential for change of the traditional way in which the customers perceive, modify, and evaluate product models in engineering applications in the field of product configuration of individualized products designed and manufactured according to specific user needs. More extensive usability study is planned to explore the combination of various presentation elements, information content enhancement, and created synergies in specific user groups.

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Extending the Theoretical Framework of Mass Customization: Initial and Adaptive Solution Space Development for High-Variety Production Environments

Frank Steiner

Abstract In today's markets, customer needs are becoming increasingly heterogeneous. In response to the diverse customer needs, companies are oftentimes forced to offer a broad product variety in order to meet the individual demands of their customers. Being confronted with such a business environment, manufacturers need to establish new business models that are capable of dealing with high levels of heterogeneity, such as mass customization. However, as offering limitless choice is economically unfeasible, manufacturers have to develop a suitable solution space by clearly defining which product variants will be offered and which options will be explicitly excluded from the firm's offering. In this context, this paper introduces the distinction between initial and adaptive solution space development (before and after market launch) and discusses the interrelation between these two modes of defining a product offering for high-variety production environments.

Keywords Mass customization · Strategic capabilities · Solution space development · Product variety · Product management

1 Introduction

Business success in general depends on a company's ability to meet the customer needs in a specific market [1]. Therefore, it is indispensable for any firm to closely monitor the needs of its customers and to develop a product offering that meets these needs [2]. However, as customer needs in today's markets are becoming increasingly heterogeneous [3], it is rather unlikely that manufacturers will be able

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to meet customer expectations with standardized, mass-produced product offerings. Instead, firms are oftentimes forced to offer a broad product variety in order to meet the individual demands of their customers [4, 5]. Nevertheless, it is important to emphasize that the development of a broader product portfolio has to be done in a careful and purposeful manner: Offering limitless choice is economically unfeasible [6]. Therefore, variety should be offered only for those product attributes, along which customer needs diverge and that can be aligned with the existing product architecture [7, 8]. Subsequently, companies, which are targeting the exploitation of heterogeneous customer needs, have to develop a solution space of available product variants that acts as a link between the diverse customer needs on the one hand and the manufacturing capabilities of the company on the other hand [4]. Salvador et al. [7] term this capability "solution space development," i.e., understanding the customers' idiosyncratic needs and deriving a suitable set of product variants from this knowledge.

The capability of solution space development does not seem to be considered yet to a large extend in the literature. This is rather surprising as the delineation of a suitable solution space appears to be a fundamental task for any manufacturer that is facing heterogeneous markets. Piller [6], for example, states that "[s]etting the solution space becomes one of the foremost competitive challenges of a mass customization company." Nevertheless, this issue has not been discussed in detail; to the best of our knowledge, there is no study available that exclusively explores mechanisms for the development of a solution space for high-variety offerings. For this reason, this paper will focus on the strategic capability of developing a suitable solution space for heterogeneous markets in the following.

By addressing the before-mentioned gaps in the literature, this paper makes several important contributions to research on new product development in high-variety business environments in general and to the field of mass customization in particular: (1) The paper defines the terms "initial solution space development" and "adaptive solution space development" and thereby contributes to an in-depth understanding of defining high-variety product offerings. (2) Furthermore, we provide a literature review on methods that allow companies to gain an understanding of the "idiosyncratic needs" of their customers [cp. 7]. (3) Lastly, the paper discusses the interrelation of initial and adaptive solution space development and derives respective managerial implications for defining product offerings for high-variety production environments.

2 Theoretical Framework for Solution Space Development

We define the term "solution space" in the context of high-variety production environments as the sum of all available product variants in a company's product offering. This definition follows the argumentation put forward by von Hippel [9], who regards the solution space as the freedom of choice that the manufacturer's production system allows the customers. In order to define this solution space, a company has to decide "what it will offer—and what it will not [provide]" [7]. This managerial decision process is necessary as offering limitless choice is economically unfeasible and the solution space has to be in line with the pre-existing manufacturing capabilities of the company [9]. The result of this task is a "choice menu" of product features or product attributes that customers can choose from in order to customize products that meet the individual customer needs [10].

Solution space development is a rather cross-functional task: On the one hand, it is strongly interlinked with the technical environment of the product, but it also has to take the respective market situation into account. This results from the fact that the solution space has to act as a link between the heterogeneous customer needs and the manufacturing capabilities of the company [4]. With regard to the technical aspects, companies have to develop a comprehensive understanding of the customization options that are technically feasible in the generation of product variety. Piller [6], for example, suggests the three generic design dimensions fit, form, and functionality as a starting point for this analysis. Customization based on fit means to manufacture a product according to measurements provided by the customer, such as body measurements or dimensions of a physical object. Customization of form relates to aesthetic aspects, such as the selection of colors, styles, applications, cuts, or flavors. The aspect of functionality addresses rather technical attributes such as speed and precision [6]. Functionality, for example, is the traditional starting point for customization in industrial markets: In this domain, machines or components have to be adjusted to fit in with an existing manufacturing system from a technical point of view [11]. However, mere technical feasibility does not indicate a business opportunity. Therefore, the idiosyncratic needs of the customers have to be considered for successful solution space development [7]. If at all, customer needs are most likely heterogeneous for some product attributes, only. Subsequently, it is not profitable to offer all product configurations that are feasible from a technical point of view [6], but companies need to identify the so-called key value attributes [12]. Generating product variety along these product attributes offers the chance of truly creating additional value for the customers [13].

This analysis indicates that there indeed is a broad body of the literature that is concerned with the realization of a mass customization strategy and respective strategic capabilities. However, despite this ongoing research on mass customization and the relevant strategic capabilities, no research so far addresses the issue of solution space development in an integrated and holistic manner. For this reason, we present a detailed literature review on the capability of solution space development in the remainder of this paper. With this research, we extend the current understanding of interrelation of defining product offerings for high-variety production environments and also provide respective managerial implications for mass customization practitioners.

2.1 Solution Space Development: A Two-Stage Process

Solution space development in markets with high levels of heterogeneity has to be clearly distinguished from defining a product offering in the context of a more homogeneous business setting [6]. As mass production aims at reaching as many customers as possible with standardized products, manufacturers have to develop products that address common needs among all targeted users. In product domains with high customer need heterogeneity, on the contrary, firms need to identify those product attributes along which customer needs diverge the most [7]. These different approaches to solution space development also cause significant differences in the role of uncertainty [14, 15]: When customer needs are highly heterogeneous, customers will most likely show varying preferences in terms of product options [16]. Subsequently, companies have to offer more product variety, which in term may lead to higher levels of complexity in all planning tasks of the value chain [17]. As complex tasks are more difficult to predict for the respective decision maker, the increase in complexity ultimately leads to a higher level of uncertainty [18].

This leads to a severe dilemma for product managers that are faced with the task of solution space development in heterogeneous markets: On the one hand, the market success of new products is contingent upon successful solution space development. Only if product managers are successful in understanding the idiosyncratic needs of the customers, an appropriate product offering, which has a chance to be successful in the respective market, can be derived [19]. On the other hand, as shown above, the impact of uncertainty on developing a solution space is particularly strong in the context of heterogeneous markets. In consequence, it becomes nearly impossible to derive a product offering that is in line with the current and future market demands at the same time [20, 21]. This dilemma causes an adaptation problem: Decision-making processes need to provide sufficient flexibility so that adjustments to the initially designed solution space can be made, as new information is gained [22]. For this reason, Tseng and Piller [23] propose a so-called knowledge loop that allows to acquire new knowledge in an iterative manner, so that the efficiency and quality of the solution space can be constantly enhanced.

It becomes apparent that product management should approach the task of solution space development for heterogeneous markets by means of a two-step procedure. Thus, we suggest to separate between tasks of "initial solution space development" and "adaptive solution space development." In accordance with Verganti and Buganza [24], we suggest to differentiate between the point of time, when the solution space is conceived for the first time in its initial form and the time after market launch, where the solution space will be continuously improved over time. This suggested dichotomy is based on the "classic distinction in organizational thinking between situations that can be described as certain, predictable, well-understood, or routine and situations that are characterized as unpredictable, intractable, or uncertain" [25]. Before market launch, the product itself does not exist yet and decisions have to be made under uncertainty [26]. However, as soon as the initial solution space has been launched to the market, performance indicators can be derived [27] and the existing solution space can be adapted whenever insufficiencies are detected. In the following, we will discuss these two concepts—initial and adaptive solution space development—in more detail.

2.2 Developing an Initial Solution Space Before Market Launch

This paper extends the definition of solution space development of Salvador et al. [7] by introducing the differentiation between initial and adaptive tasks of delineating a suitable product offering. In this context, initial solution space development is defined as the sum of all product management activities that are necessary to define those variants of the new product that will be made available at market launch. While this may consist of tasks such as the elicitation of customer needs and the selection of necessary product features, solution space development does not include any product design activities nor the definition of an underlying product architecture. This definition clearly indicates at what time companies need to engage in initial solution space development activities: For every new-to-the-firm product and for every new-generation product, an initial solution space needs to be defined before the new product offering is introduced to the market.

The fact that the initial solution space has to be drafted before market launch brings about a specific characteristic of this phase in product management: As the product has not yet been released to the market, the product itself does not exist at the time when the respective decision-making process takes place. That means that the customers, on the one hand, cannot interact with the new product itself, but can only experience a mere verbal description or a prototype and are thus not able to provide fully accurate feedback concerning the new product [28]. The manufacturer, on the other hand, does not have access to realistic data on customer demand and purchase behavior [29]. For these reasons, neither the company nor the potential customers can benefit from existing usage experience or objective product data [26]. Subsequently, the initial product offering has to be derived under conditions of high uncertainty, and it is very unlikely that a manufacturer can indeed define an ideal initial solution space under these circumstances. It is simply not possible to predict all technological advances and changes in customer demand [30].

We suggest two major objectives that are relevant for initial solution space development: Firstly, manufacturers need to assess which product design parameters are relevant and feasible in the context of the solution space development process at hand. In this context, "[d]esign constraints may be functions of the laws of nature, the environment in which the product will function, governmental regulations, or corporate decisions or policies" [31]. These restrictions need to be considered, as an economically efficient production can be realized only, if all predetermined product options in the solution space meet the preexisting capabilities and resources of the company's manufacturing system [9]. The result of this assessment should be a collection of all product variants that could realistically be provided by the specific manufacturer. Secondly, the company has to identify the customer requirements for the respective product domain [31]. For this purpose, companies have to understand the customers' idiosyncratic needs and derive a suitable set of product variants that corresponds with the heterogeneous customer demand [7]. After deriving all relevant and feasible product options and identifying the customer requirements, these two sets of product variants can be compared. In consequence, the sum of all congruent elements will form the initial solution space.

These two objectives already provide rough guidelines for the execution of initial solution space development. However, it remains unclear, how companies should approach these two objectives operatively. Therefore, we will derive suggestions for particular methods or managerial activities, which could be applied for defining an initial product offering, from related knowledge domains. With regard to the first objective mentioned above—the identification of all relevant and feasible product design parameters—companies could adopt managerial approaches from several related fields, as this decision is influenced by technical, economical, and normative limitations [31]. One very well documented approach for understanding the technical as well as economical limitations of the product at hand could be the application of the so-called quality function deployment (QFD) method. QFD originally is a method for transferring customer needs into technical product specifications [32]. However, the approach builds on the use of transformation matrices that enable decision makers to visualize the relationships among individual product specifications [33]. That way, trade-offs between certain product attributes or parameters can be identified and technical limits in the generation of variants can be revealed [33]. Besides the technical and economical limitations, initial solution space development also needs to take normative limitations in form of laws, regulatory standards, or social norms into account. Certain industrial standards, for example, could specifically prohibit product variety with regard to specific parts or components [34]. Furthermore, certain technologies might be protected by patents and have to be excluded from the feasible solutions or require licensing before they can be considered in the respective solution space. In this context, patent analysis might be a suitable methodological approach to make allowances for these normative limitations [35].

Beyond identifying potential limitations of the respective product offering, initial solution space development also has to build up an understanding of the relevant key value attributes in the market [12]. From a methodological perspective, most conventional market research techniques could be applied for this purpose. However, due to the high level of heterogeneity in customer needs, companies might have to refrain from using such methods, as they have been developed for the purpose of revealing "average" customer needs, i.e., finding commonalities among potential customers [36]. In heterogeneous markets, however, companies should try to identify the differences in customer needs [7]. Similarly, Ogawa and Piller [37] claim that common market research techniques are not administrable in the case of high levels of customer need heterogeneity and high numbers of possible product variants. Subsequently, market research methods have to be refined in order to be applicable in today's changing market environment [38].

Furthermore, the identification of customer needs might be hampered by the fact that the customers oftentimes simply do not know what they really want in a product [37]. For example, latent needs may not be mentioned by the customers, because they are considered to be a basic prerequisite and might be taken for granted. Other need information may not be transferred as customers are either not able to correctly express these needs or they are not aware of them [20]. In such a context of low preference insight, initial solution space development needs to implement specific organizational processes and methods in order to proactively learn about the latent needs of current or potential customers [27]. For this reason, the literature suggests different market research techniques such as focus groups, conjoint analysis, or customer surveys [33]. In particular, the conjoint analysis seems to be a suitable methodological approach to capture the heterogeneity of customer needs concerning specific product attributes [39, 40]. Some researchers have developed methods for solution space definition which build on a conjoint analysis methodology. Here, the approach is not used to identify the best product variants, but options in a solution space that will be valued most by customers [10].

Also, as customers might not fully understand the opportunities that arise with new, disruptive technologies, they might orient themselves at the status quo of technology when voicing their needs [41]. Subsequently, in order to avoid misleading suggestions, companies may focus their market research activities on specific users that have more technological know-how and that can make well-informed and foresighted suggestions for new products. This is a similar view of the customer as in the lead user concept put forward by von Hippel [42, 43]. Lead users have well-expressed, current preferences that are ahead of the market and that will become common needs of many customers in the future. Lead users are not only aware of their needs, but they also have solutions for their own problems. Furthermore, these users are willing to pass their solution knowledge to manufacturers and thereby actively contribute to the development of new products [44].

2.3 Adapting an Existing Solution Space

Whereas initial solution space development aims at defining a suitable product offering before the time of market launch, adaptive solution space development is defined as the sum of all management activities that are concerned with the assessment of the market fit of the existing solution space and potential changes to this offering. For this purpose, an organization should constantly evaluate the fit of any exiting solution space with the heterogeneous customer demand within its product domain. In case, the existing solution space does not show a sufficient level of fit, the organization needs to revise, trim, or extend the available product assortment in order to comply with changing customer needs and/or new technologies [7]. If such an adaptation of the solution space should become necessary, this could manifest itself either in the introduction of new product variants that meet new or previously undetected needs or in the elimination of underperforming existing variants [17, 45].

In comparison with the phase of initial solution space development, there is much more information available for the tasks of adaptation. As these management activities only become relevant after market launch, there already is, by definition, an existing product offering in the market and the manufacturer and the customers can gain experience by interacting via this solution space. That means that on the one hand, customers can benefit from a real-life customer experience of actually searching and buying suitable product variants from the solution space [24], whereas the manufacturer, on the other hand, now has objective sales data available that can be analyzed for the purpose of adaptation [27]. Such sales performance data does not only reveal how often each product variant was sold, but it could also provide detailed information about the configuration and sales process, which could be used to reveal potential pitfalls or shortcomings of the transaction processes in use [46]. Thus, the level of available information is much higher during the adaptation process than during the initial development of the solution space, and subsequently, managers are not facing such high levels of uncertainty during adaptive solution space development.

Similar to initial solution space development, there are two major objectives that have to be addressed in the context of adaptive solution space development. The first objective is concerned with the fit between the existing solution space and the current customer demand in the respective market. Before any corrective action can be taken, the level of fit needs to be measured or controlled in some way. For this purpose, companies need to identify proxy variables that could serve as an indicator of the quality of the existing product offering. Only if such a controlling mechanism has been established, companies can identify shortcomings of their existing solution space. Salvador et al. [7] call this process of collecting and analyzing data on customer transactions, behaviors, and experiences "customer experience intelligence." The second central objective of adaptive solution space development is the tracking of social trends or new technological developments. As the necessity for adapting the solution space can result from unexpected changes in customer preferences [47] or technical turbulences [48], companies should try to keep track of these developments, so that they can better predict upcoming changes of their business environment.

This discussion of objectives of adaptive solution space development leads to the question, which methods or management activities could be applied in order to fulfill the above-mentioned goals. The first objective of adaptive solution space development is the constant assessment of the fit between the existing product offering and the current customer needs. As the term "customer experience intelligence" [7] indicates, this task builds upon the fact that there already is an existing product offering available in the market, and that customers can interact with real products and can experience these products in a real usage environment. This experience, in turn, may lead to new suggestions for improvement [49]. It is the companies' task to collect these suggestions, so that they can react to these customer impulses and adapt the existing product offerings, if necessary. For this purpose, the manufacturers have to enable their customers to express their concerns about the existing product offering. Methods for enabling the customers to transfer this information range from simple feedback forms or questionnaires to regular workshops with key customers [50]. Also, companies can make use of Internet-based technologies such as toolkits or feedback mechanisms within the configurator [51] or can interact with customers via key account management systems [52]. In this context, it is important to notice that companies should not rely on only one way to gather such customer feedback, but should provide multiple channels for this interaction with customers [50].

Besides managerial activities for gathering direct customer feedback, there are also methods that can serve as indicators for the quality of solution space fit in a more indirect manner. One possibility in this context is the analysis of sales data of the current product offering. If such an analysis should reveal that certain product variants are performing rather poorly, product management should consider to eliminate the respective options from the product offering as the maintenance of each option that is kept available causes substantial costs [53]. Another potential indicator for the fit of the existing solution space can be seen in the actual customer behavior within the customization process, especially if the existing product offering is available in an online configurator. In such a case, log files of the customers' browsing behavior—i.e., number of hits, the search history, or the amount of time that was spent on a certain Web site—can be used for the purpose of refining the solution space [7, 54]. Using these data, a simple analysis of hits can already provide information about the popularity of certain features, and particularly long page impression durations of individual pages could indicate that there are certain pitfalls or shortcomings within the existing product offering [7].

In order to derive a solution space that meets current and future challenges alike, it is imperative for product managers to apply corporate foresight to forecast future developments of a company's business environment [55]. In this context, the second objective of adaptive solution space development is the tracking of social trends and new technological developments, in order to detect changes in customer preferences or technical turbulences as early as possible. Strategic management literature offers several managerial approaches for forecasting activities, which help companies to identify such disruptions of the business environment and to turn them into business opportunities [56]. Research shows that most corporate foresight activities, which are applied by product managers, aim at the identification of new customer requirements by analyzing cultural shifts and gathering new information about customer needs [55]. Examples for such methods are, for example, the analysis of interest groups such as online brand communities [57, 58] or the use of lead user methodology [42, 43]

As mentioned above, the second important aspect of this task is the identification of emerging technologies by scanning the technological environment of the product domain [55]. For this purpose, firms can apply rather simple methods such as technology road maps [59] or more complex approaches such as scenario analysis [60]. Scenarios consider many aspects such as stakeholder information, technology road maps, key uncertainties, or social trends at the same time and try to reduce this enormous amount of information into a limited number of possible scenarios, which are documented in narratives that are much easier to understand and grasp for the respective decision makers [61]. Rohrbeck and Gemünden [55] show in their study that about two-thirds of the companies in the study sample employ some form of a continuous technology-scanning activity, ranging from technology road mapping to individually developed tools for the evaluation of potentially applicable technologies. Normally, such tools aim at monitoring a certain number of technologies and providing an assessment of the level of maturity and deployment readiness of each of these technologies [55].

2.4 The Interrelation of Initial and Adaptive Solution Space Development

After discussing the two modes of solution space development in more detail, this chapter will try to shed light on the interrelation of the two concepts. This paper conceptualizes initial and adaptive solution space development as tasks that take place at different point of times during new product development. As the product itself only becomes available at the time of market launch, initial and adaptive solution space development are also characterized by different levels of uncertainty: Defining an initial product offering is subject to high levels of uncertainty, whereas the adaptation of the existing solution space can benefit from additional information that becomes available after market launch. Based on these considerations, the two modes of solution space development could be viewed as two sets of tasks that compete for the same resources in the context of defining a suitable product offering. This argumentation identifies a management trade-off in solution space development: Companies have to decide how much effort they would like to invest in the initial development of the solution space. Presumably, a higher investment at an early stage enables the company to avoid costly adaptations after market launch. However, this reasoning diminishes the role of adaptive solution space development and describes it as a mere corrective mechanism that makes up for "mistakes" have been made during the definition of the initial product offering.

However, in contrast to this evaluation, we rather regard initial and adaptive solution space development as complementary tasks that supplement each other: On the one hand, certain decisions during the definition of an initial product offering may affect the adaptability of the solution space at a later point of time. For example, a company's decision to use a certain technology for a new product family might prohibit a change of technologies at a later point of time. However, if the company considers flexible interfaces during the initial conceptualization of the product, adaptations of the resulting solution space may be realized with less effort. On the other hand, adaptive solution space development is the only way to integrate new technologies or to consider trends in customer demand, which could not be foreseen at the time of market launch. Subsequently, this mode of reconsidering the existing product offering cannot be downgraded to a purely corrective mechanism, but it should be carried out in a more proactive manner. Subsequently, an optimal product offering can only be realized by balancing initial and adaptive solution space development tasks in an integrated product management concept.

Having recognized these complementarities among initial and adaptive solution space development, research in this field might be able to benefit from related literature that describes similar interrelations. For example, product development literature considers a similar complementary interrelation in the context of organizational learning. Organizational learning literature separates all possible organizational activities into two categories: exploration and exploitation [62]. Thereby, exploration describes all activities that engage in the pursuit of unknown things and the integration of these aspects into the knowledge of the firm. Exploitation, on the other hand, indicates actions that aim at the use and refinement of existing knowledge [cf. 62, 63]. Similar to initial and adaptive solution space development, activities of exploration and exploitation compete for the same resources in an organizational context. Therefore, companies have to decide how to balance their investments in either set of activities. With regard to this trade-off between exploration and exploitation, research observes "a tendency to substitute exploitation of known alternatives for the exploration of unknown ones, to increase the reliability of performance rather more than its mean" [63]. However, such a focus on exploitation activities will inevitably destroy the competitive position of any company in the long run, as innovation and renewal are essential for the future viability of a company [62]. Therefore, it is necessary for organizations to find a suitable balance between exploitation and exploration. A broad stream of management literature is concerned with such a balanced approach to exploitation and exploration, namely organizational ambidexterity. Ambidexterity describes a firm's capability to successfully manage the daily business while simultaneously being able to identify and adapt to new developments in the business environment [64]. Subsequently, companies have to become ambidextrous organizations in order to find the necessary balance between exploration and exploitation. For this, organizational structures and strategies may have to be reconsidered, as they are considered important promoters of ambidexterity [64].

This analogy from the organizational learning literature provides valuable insights for the development of suitable solution spaces for heterogeneous markets. Comparably to exploration and exploitation, initial and adaptive tasks of solution space development have to be balanced in order to enable long-term success. For this purpose, firms have to accept that adaptive solution space development is more than just a corrective mechanism and should view the adaptation of existing product offerings as an opportunity rather than a threat. However, such a shift in the strategic mindset of a company might require fundamental changes to the organization, just like in the case of companies that strive for becoming an ambidextrous organization. Companies that struggle with this transition toward higher levels of operational flexibility can follow the recommendations and managerial implications of agile manufacturing research [cf. 65–67]. The term "agile manufacturing" describes the ability of a manufacturer to successfully offer a range of products, even though being exposed to market conditions of continuous change [65]. Agility "requires flexibility and responsiveness in strategies, technologies, people and systems" [66]. In this context, Yusuf et al. [67] even claim that agile manufacturing goes beyond high levels of responsiveness or flexibility, but rather has to be considered as an orchestrated use of many different flexible production technologies and insights from manufacturing practices such as lean production. Subsequently, a company that has adopted the principles of agile manufacturing will be empowered to truly benefit from the complementarities of initial and adaptive solution space development.

3 Conclusion

This paper discusses the development of product offerings for heterogeneous markets that demand high levels of product variety. So far, there are no studies available that discuss the concept of solution space development with this level of detail or that provide recommendations for potential activities or best practices in this field. Therefore, it can be stated that this paper contributes to the product management research in several ways: Firstly, the paper extends the existing definition of solution space development by defining the terms "initial solution space development" and "adaptive solution space development," two different modes of defining a product offering for heterogeneous customer needs. Beyond the theoretical conceptualization of these two approaches, the paper provides an extensive literature review on methods and tools for defining suitable high-variety product offerings. Secondly, the paper provides a valuable contribution with regard to the interrelation of initial and adaptive solution space development. In this context, the paper shows that—similar to the concept of ambidexterity in organizational learning—initial and adaptive tasks of solution space development have to be balanced in order to enable long-term success of a respective product offering. With this finding, we make a useful contribution to the managerial implications for the realization of successful solution space development, as our results highlight the need for highly flexible and responsive strategic and operational processes as a basic prerequisite for defining a successful product offering for high-variety environments.

Furthermore, the results of this paper could serve as a starting point for future research in this field of expertise. In the following, two potential gaps that require further research will be highlighted. Firstly, the validation of the theoretical concepts that were developed in this paper could be strengthened with respective qualitative or quantitative empirical evidence. For this purpose, it would be useful to conduct expert interviews or a large-scale survey among manufacturers of high-variety product offerings. Secondly, future research could try to investigate the impact that individual managerial activities mentioned in this paper have on the solution space quality/fit or on the overall firm performance.

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Flexible Laser Metal Cutting: An Introduction to the ROBOCUT Laser Cutting Technique

Sigurd Villumsen, Steffen Nordahl Joergensen and Morten Kristiansen

Abstract This paper describes a new flexible and fast approach to laser cutting called ROBOCUT. Combined with CAD/CAM technology, laser cutting of metal provides the flexibility to perform one-of-a-kind cutting and hereby realises mass production of customised products. Today's laser cutting techniques possess, despite their wide use in industry, limitations regarding speed and geometry. Research trends point towards remote laser cutting techniques which can improve speed and geometrical freedom and hereby the competitiveness of laser cutting compared to fixed-tool-based cutting technology such as punching. This paper presents the concepts and preliminary test results of the ROBOCUT laser cutting technology, a technology which potentially can revolutionise laser cutting.

Keywords Flexible automation · Laser cutting · One-of-a-kind production · 3D cutting · Free form cutting

1 Introduction

Companies are today faced with an increasing demand for fulfilment of individual customer needs, and this results in an increasing number of product variants and/or customised products. Mass customisation (MC) [1] focuses on how to operate in and take advantages of such market conditions, including how to deliver and

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manage high product variety and customised products. An essential element in MC is to limit the internal complexity of product variety, e.g. by modularisation and postponement of the product decoupling point. From a review of MC literature, [3] appoints the importance of process agility, both in a definition of MC and in a list of MC enablers. This has been supported by a later study conducted by [14]. Based on [1] and substantial MC implementation experiences, [14] appoints robust process design as one of three essential capabilities for a company to succeed with MC. In terms of manufacturing, robust process design can be interpreted as a manufacturing system capable of absorbing fluctuations, varieties and changes in manufacturing requirements. Hence, manufacturing systems should, regardless of MC, possess flexibility to handle product variety, customised products and constant product introductions.

In regard to metal cutting, laser cutting is one such flexible process technology which, in combination with CAD/CAM, is capable of performing one-of-a-kind metal cutting and hereby realises customised products. A main advantage of laser cutting over other flexible types of metal cutting, e.g. water or plasma cutting, is its cleanliness and its ability to create cuts that can accommodate the high demands for surface finish that is, e.g. present in the automotive industry. Laser cutting is a widely used technology and can be found in many industrial applications [4, 16].

Since the first oxygen-assisted laser cut was accomplished in 1967 [18], the CO_2 laser has been the most common laser type for cutting applications [23], as it was able to provide the required power for metal cutting. It is still a widely used technology, but due to the wavelength of the generated laser beam, it needs to be guided by means of mirrors from the laser source to the workstation. This reduces the flexibility of the system and increases the cost of a reconfiguration of the laser cell.

Recently, new types of high-power lasers have emerged, such as the single- and multi-mode fibre lasers and disk lasers [6]. These laser types have much higher energy efficiency while retaining the exceptional beam quality of the CO_2 laser [10, 20]. Another benefit is that these laser types have a shorter wavelength which entails that they can use optical fibres for beam guidance instead of mirrors. This gives a great deal of flexibility as the laser power can be fibre-transmitted from a central laser station to one or more workstations in the production facility.

In standard laser cutting, the molten material is removed by a cutting gas delivered through a nozzle. This implies a strict process restriction on the distance between the laser cutting head and the object to be cut. This restriction results in speed and geometrical limitations of laser cutting and hence a lack of competitiveness compared to fixed-tool-based high-volume processes such as punching. As stated in [9], the limitation on current cutting speeds in industrial sheet cutting applications is, however, no longer due to the intensity of the laser, but due to limitations of the mechanical set-up that is used to move the work piece and the laser. This has led to a substantial amount of research being conducted within the field of remote laser cutting where the movement of the laser beam is no longer based entirely on the reposition of the cutting head, but also on the deflection of the beam by means of mirrors, e.g. [7, 17, 25]. In [9], it is, however, pointed out

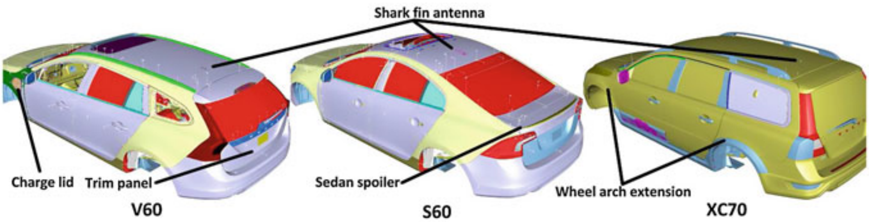

Fig. 1 Schematic showing three different Volvo models, each with cuts made for various accessories. The above car models have been provided by the courtesy of Volvo

that remote laser cutting is still in an early stage of development and is still suffering from burr formations and thickness limitations. The main challenges with these remote cutting technologies are related to their ability to eject molten material from the cutting kerf. The ROBOCUT technology described in this paper is a new way of conducting remote laser cutting that has the potential to overcome these disadvantages and increase cutting speeds and reduce burr formations.

1.1 Volvo

The applicability of the ROBOCUT technology and good-quality remote cutting in the industry is very large, especially with regard to customisation of prefabricated sheet metal panels. As an example of such an application of remote laser cutting and the ROBOCUT technique, one could look at the automotive industry. One of the main advantages that remote laser cutting can accomplish over other cutting techniques is to introduce customisation of end-user products at a very late stage of production. This is mainly due to its flexibility and its ability to cut complex shapes in 3D objects, e.g. a car chassis. In Fig. 1, three different Volvo models are shown. All of these models can be equipped with various accessories, depending on package and market for the model. Traditionally, cutting the required holes/ contours for these accessories would require cutting in the body shop before prepainting. By introducing good-quality remote cutting via, e.g. the ROBOCUT technology, it is possible to move the cutting of these mounting holes to a very late stage of production, possibly to the steps of final assembly. This implies that the product decoupling point can be postponed to the stage of final car assembly.

In the following section, a small introduction to laser cutting, including remote laser cutting, will be conducted. In Sect. 3, the ROBOCUT technology will be described; preliminary results will be discussed in Sect. 4, and Sect. 5 draws up the conclusion.

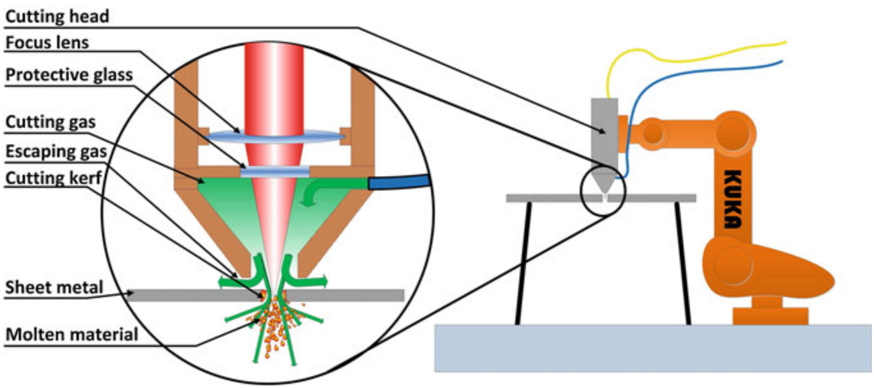

Fig. 2 A sketch of traditional laser cutting. A laser beam (*red*) melts the sheet metal being cut (*grey*), and a cutting gas (*green*) is applied to blow away molten material from the cutting kerf (Color figure online)

2 Introduction to Laser Cutting

The process of cutting materials with a high-power laser beam is known as laser cutting. It can be used to cut a large range of different materials ranging from, e.g. thin wooden plates, to high-strength steel. Depending on the type of laser, even transparent materials like acrylic can be cut. The principle of the process is simple, and you take a high-power laser source, focus it and move it over the target that needs to be cut. If the target is made of, e.g. metal, it will melt and evaporate, and if it is made of, e.g. plastic or wood, it will evaporate and burn. One of the main difficulties with metal cutting is that the molten metal will start to solidify as soon as the laser beam is turned off or has moved away. If the molten material is not removed from the cutting kerf, it will solidify where it was and simply close the gap behind the laser beam, and thus, a proper cut will not be obtained. This entails that for a good cut, the molten material needs to be removed efficiently. In the following, laser cutting will be divided into two categories, traditional laser cutting (see [18]) and remote laser cutting (see [9, 26]), due to their fundamental differences in how the molten material is removed and how cutting is achieved.

2.1 Traditional Laser Cutting

In traditional laser cutting, a laser beam is focused on the metal sheet that needs to be cut (see Fig. 2). The intensity of the laser beam heats up the metal, and it melts, evaporates and sublimates (phase transition from solid directly to vapour state). To prevent the molten material from solidifying on the sides of the cutting kerf, a gas (e.g. nitrogen) jet is applied to blow it away [2, 13, 15]. Some of the cutting gas escapes through the gap between the nozzle tip and the metal, and the rest enters

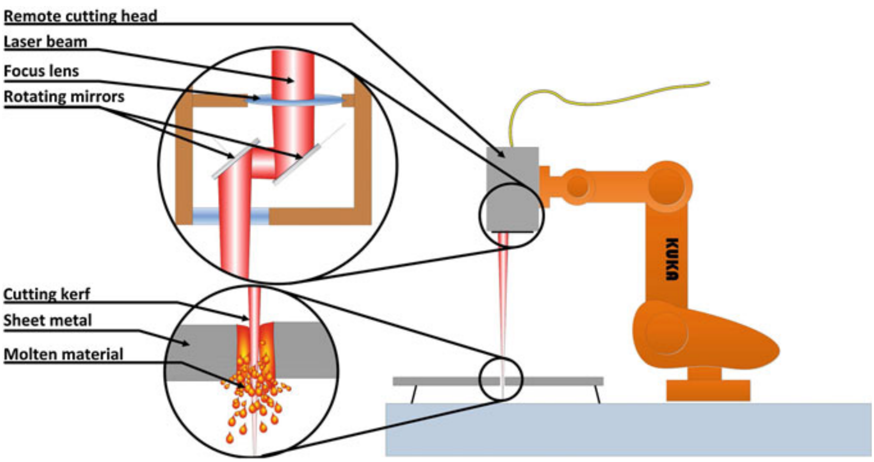

Fig. 3 A sketch of remote laser cutting. A laser beam (*red*) is deflected by two mirrors and cuts a piece of sheet metal underneath. Note the remote position of the cutting head (Color figure online)

the cutting kerf and blows away the molten material. Using a cutting gas for melt ejection ensures that good cutting quality is obtained as the melt ejection can be controlled by the gas pressure. The main drawback besides the cost of cutting gas is that the gas nozzle needs to be positioned close to the object to keep a constant gas pressure to the cutting kerf. Another limitation is that the focusing optics and gas nozzle and other pieces of equipment are combined in a cutting head. The cutting head needs to be moved over the entire contour, which practically limits the cutting speed to the speed of the mechanical system that repositions the cutting head. Also, if a contour needs to be cut on a complex 3D shape, it might be geometrically impossible to find a path where the cutting head does not collide with the object. Another inherent trade-off when using a cutting gas is that on the one hand, the narrower the cutting kerf gets, the faster the gas pressure will drop in the cutting kerf. This results in less gas flow to blow away molten material and thus worse quality. On the other hand, when the cutting kerf decreases in width, the amount of metal that needs to be melted also decreases, which again entails that faster cutting rates can be achieved with the same laser power. These drawbacks and trade-offs have entailed that a lot of research is being done in how remote cutting can be achieved [9, 26].

2.2 Remote Laser Cutting

In remote laser cutting, the cutting head is no longer positioned adjacent to the sheet metal but at a distance. This remote position entails that the risk of collisions can be reduced. A remote cutting set-up is shown in Fig. 3 where two rotating mirrors are

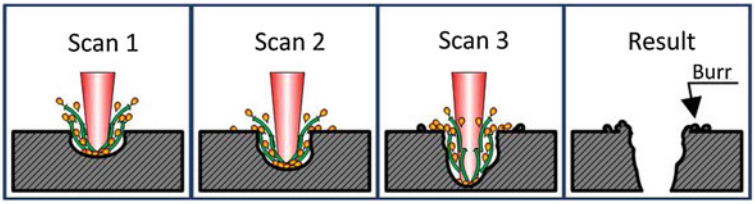

Fig. 4 Schematic showing the principle of RAC of sheet metal (*grey*). The laser beam (*red*) melts the metal (*orange*) and creates a vapour pressure (*green arrows*). The melt is ejected by means of the vapour and to some extent solidifies as burr on top of the cutting kerf (Color figure online)

used to deflect the beam. For simplicity, some components of the cutting head are not shown in the figure, e.g. collimating lens and focus adjustment. The main advantage of remote cutting is that the beam can be repositioned by means of an optical system, e.g. scanner mirrors, instead of a standard mechanical repositioning system. These mirror-based systems allow for very fast beam repositions exceeding >720 m/min [26]. The main drawback is, however, that the molten metal can no longer be removed by means of a gas nozzle, and currently, there are two processes by which the molten material can be removed, and these are remote ablation cutting (RAC) and remote fusion cutting (RFC) [26].

In RAC, a highly focused high-power laser beam moves over the contour that needs to be cut at a very high speed repeatedly. On each pass, the beam melts and evaporates only a tiny bit of the surface metal as shown in Fig. 4. The main principle is that in the cutting kerf, the evaporated material expands and builds up a gas pressure that ejects the molten material when the gas escapes the cutting kerf. By repeating this process, more material is removed, and if enough scans are conducted, the material will finally be cut. This technique generally allows for fast cutting speeds in thin plates, but the speed quickly decreases when the thickness increases.

In RFC, the melt ejection mechanisms are not completely understood yet [26]. In this type of remote cutting, an unfocused laser beam is moved slowly over the sheet metal. Due to the intense heat and the evaporation of metal on the top of the cutting kerf and internal pressure phenomena, the molten material is expelled from the cutting kerf. The main drawback of RFC is the slow cutting speeds and the large heat-affected zone (HAZ). The HAZ is a zone around the cutting kerf where the metal has been heated to such a degree that the internal metallic structure changes. These changes can cause several disadvantages such as changes in hardness and increased risks of ruptures [19]. Both technologies have, however, difficulties when cutting thicker plates when compared to traditional laser cutting. According to [11, 26], RFC with a 4-KW laser can only cut 3-mm stainless steel, which is not a lot when compared to standard laser cutting. In [8], a weaker (3 kW) laser can cut plates more than three times as thick and at much faster speeds when an external cutting gas is applied. Both technologies rely on some form of gas pressure being generated directly by the intense laser radiation in the cutting kerf. These mechanisms are exactly what the ROBOCUT approach seeks to enhance and control.

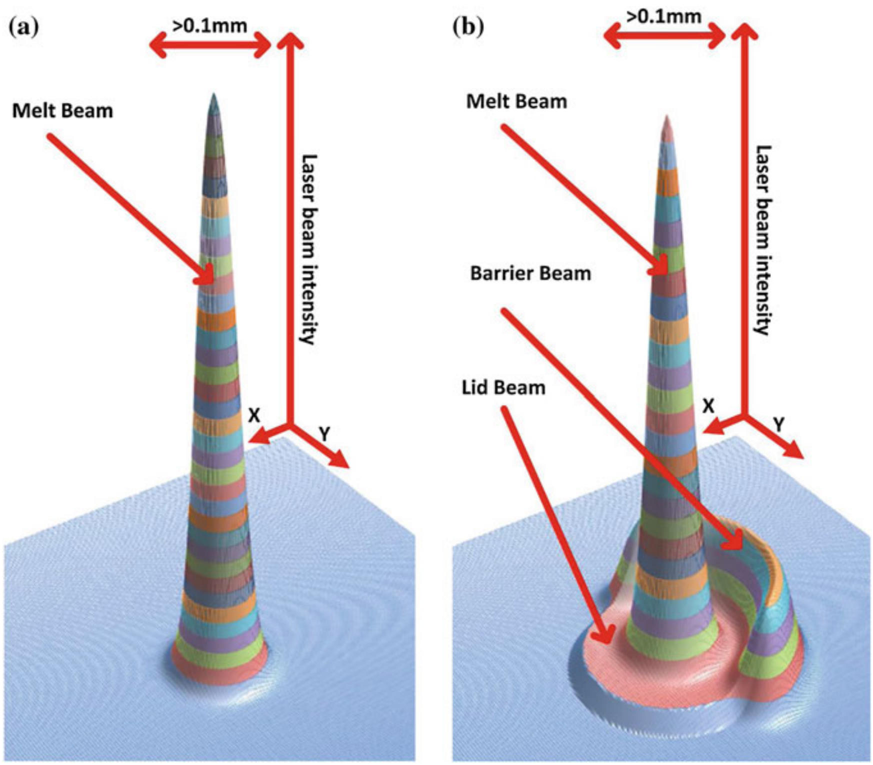

Fig. 5 Intensity distribution of a SM laser beam (**a**) and a concept of the ROBOCUT beam (**b**). **a** Shows the intensity of an ideal single-mode laser beam. **b** Shows the intensity distribution of the proposed ROBOCUT laser beam

3 ROBOCUT Laser Cutting

The ROBOCUT approach seeks to improve the melt ejection mechanisms to RAC and RFC. The idea is that by changing the intensity distribution of the beam, the melt ejection mechanisms can be controlled [11, 12]. A beam from a single-mode fibre laser will generally have an intensity distribution with a shape that reassembles a Gaussian function. Such a standard distribution is shown in Fig. 5a. In Fig. 5b, the concept of the ROBOCUT beam is shown. When this is compared to 4, it is shown that the laser beam has been divided into three beam sections: a melt beam, a barrier beam and a lid beam. This division implies that only a part of the beam should be used for melting the metal, and the remaining should be used for melt guidance in the cutting kerf. In Fig. 6, the principle of a ROBOCUT laser cut is shown. The melt beam is where the majority of the laser power is placed as it is used for melting and evaporating the metal. When the cutting head moves, the molten metal runs (blue arrows) around the melt beam due to the evaporation of metal on the front side of the cutting kerf. As the head moves further down the

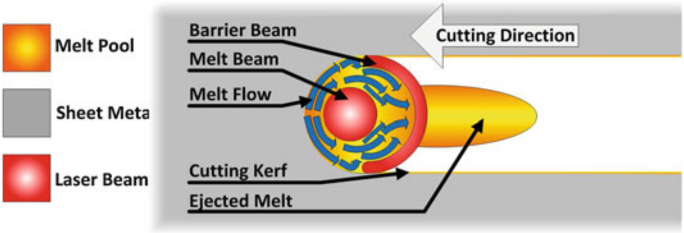

Fig. 6 Schematic showing a concept of how the melt flow would be with the cutting beam from the ROBOCUT project

contour, this metal is met by the barrier beam. The barrier beam creates a vapour pressure that pushes the molten metal from the sides of the cutting kerf towards the centre to prevent it from solidifying on the sides. Finally, the lid beam creates a vapour pressure on top of the cutting kerf that pushes the molten material downwards and out of the cutting kerf. The main advantage of using multiple beams instead of one is that the ejection gas, which is normally added from a gas nozzle, is directly generated by the barrier beam and lid beam. By doing this, the trade-off described in Sect. 2.1 between kerf width and gas pressure can be avoided. This ensures that a good melt ejection can be created, even in very narrow cutting kerfs. This should lead to an increase in cutting speed and thickness capability when compared to RFC and RAC. The quantity and direction of the generated ejection gas can be customised by changing the design of the beam pattern. If a proper beam design can be found, remote cutting can be achieved in a single pass as with RFC but potentially at much higher speeds [10]. Another possibility with the ROBOCUT approach is that the vapour pressure, generated by the beam pattern, can be combined with an external gas source to improve the melt ejection of standard laser cutting. This could lead to an increase in cutting speed and a reduction in burr formations. On this basis, a preliminary estimation of the cutting potential has been conducted by [10] where it is assessed that speeds can be almost doubled compared to standard laser cutting when the internal gas generation is combined with a standard cutting gas.

3.1 Technology Comparison

As stated in the introduction, the above-mentioned laser technologies (standard laser cutting, RAC, RFC and ROBOCUT) are all to some extend flexible manufacturing processes, as they can be controlled by CAD/CAM software to produce customised products. If one considers the Volvo case described in Sect. 1.1, one of the main goals is to implement this customisation process at an as late manufacturing step as possible to minimise internal product variety. It has already been stated that laser cutting and especially good-quality remote laser cutting would be

Table 1 Various pros and cons regarding cutting techniques

	Water jet	Plasma	CO_2 laser	Fibre laser	RAC	RFC	ROBOCUT (remote)
Process mess	High	Medium	Low	Low	Low	Low	Low
Speed (1-mm SST) (m/min)*	<10	<22.9	<40	>40	–	10	70
Speed (0.5-mm SST) (m/min) *	<10	<22.9	>40	>40	100	No data	>100
Max thickness (mm)	–**	–**	–**	–**	0.7	3	6 ***
HAZ	None	High	Low	Low	Low	High	Low
Initial cost	Medium	Low	Medium	Medium	Medium–high	Medium–high	Medium–high
3D cutting	(–)*****	(–)*****	(–)****	(–)*****	Yes	Yes	Yes

The majority of these data are taken from [10, 21–24]
*The speed values are taken from typical production cutting set-ups. Much faster cutting speeds have been seen in research applications. These applications are mainly limited by the mechanical repositioning system and not the laser power
**Maximum thickness mainly limited by power of, e.g. laser or water pump, and not by process limitations
***(>50 if combined with gas jet)
****Difficult due to mirror guidance
*****Low speed limited by cutting head

technologies that could postpone the product decoupling point. For easy reference, a list of capabilities of the various technologies is given in Table 1.

The table shows that in general, laser processes are relatively clean and can generally accommodate for fast processing speeds. It is also shown that the remote laser cutting technologies have the potential to achieve the fastest cutting speeds in thin sheets due to the mirror deflection of the beams. This high speed, combined with little process mess and the possibility of 3D cutting, is what drives the industry towards remote cutting. From the table, it is also shown that the ROBOCUT technology potentially can compete with the speeds of RAC cutting while retaining the ability to cut thicker sheets. When compared to water jet cutting and plasma cutting, these benefits do, however, come at a greater cost. For ROBOCUT cutting, the cost is, however, comparable to other remote laser cutting set-ups. In the following, some preliminary results of the ROBOCUT technology will be presented.

4 Preliminary ROBOCUT Results

As the ROBOCUT beam patterns are still being developed, no conclusive data have been produced that directly show the effect of the ROBOCUT technology. Preliminary results have, however, shown that there are differences and that the cutting quality is generally improved, and these preliminary studies have, however, also shown that the barrier beam shape is too wide in the current design. This entails that the ends of the barrier beam will simply heat and melt the sides of the cutting kerf and not guide the melt towards the centre and prevent it from

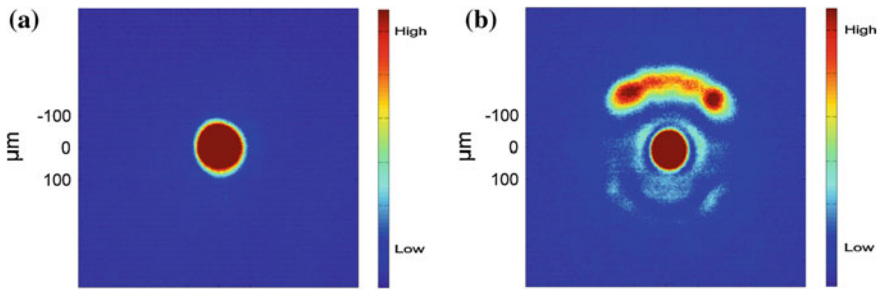

Fig. 7 Measurements of laser intensity distribution. The colours show the beam intensity, truncated to show more details. Measurements were generated by the beam analysis camera described in [5]. **a** Intensity distribution of AAU SM fibre laser. **b** Intensity distribution of the multibeam

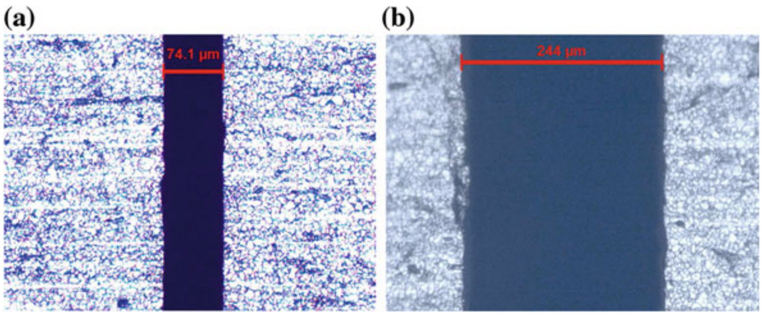

Fig. 8 Images of cuts in 1-mm stainless steel (SST EN X4CrNi18-10) with a focal length of 300 mm and with 800 W laser power. Both cuts are done with nitrogen as shielding gas at a pressure of 5 bar. **a** Shows a section of a cut in 1-mm stainless steel from a standard round beam. (**b**) Shows a section of a cut in 1-mm stainless steel with the preliminary beam design

solidifying before it leaves the cutting kerf. From Fig. 7b, an actual measurement of the shape of the laser beam is shown. It is shown that it reassembles the shape given in Fig. 5b, but with minor deviations around the centre beam.

These variations originate from the lid beam, as it, due to its low power level, is hard to distinguish from measurement noise. The nonuniform shape is a consequence of unintended interference patterns originating from the multibeam generation process or from the measurement device itself. From the figure, it is shown that the approximate width of the pattern is about 400 µm. In Fig. 8a, b, two sections of a laser cut are shown. Figure 8a shows a cut with a standard round beam, and Fig. 8b shows a ROBOCUT cut, with the beam shown in Fig. 7b. From the figures, it is shown that the cutting kerf from the ROBOCUT cut is approximately three times wider than the standard cut. This result indicates that the intensity of the beam is spread over a too wide area, and thus, a wider cutting kerf is created, which results in reduced cutting speed for the initial design.

5 Conclusion

Laser cutting is a flexible cutting process which can conduct one-of-a-kind cutting. Traditional laser cutting techniques possess a number of restrictions, resulting in speed and geometrical limitations and hereby a lack of competitiveness compared to fixed-tool-based high-volume cutting processes such as punching. This paper has presented the general idea behind the ROBOCUT technology and the main advantages of it and how it distinguishes itself from the traditional types of remote laser cutting. For easy reference, a list of capabilities of the various technologies is given in Table 1. From this table, it is clear that ROBOCUT is capable of expanding the benefits of remote cutting to thicker plates and possibly also at higher speeds.

The multibeam principle was presented, and it was shown that a tailored beam has been created. The preliminary results have shown that the new beam shape has altered the cutting process. They have, however, also revealed that the current beam design is too wide and that a new beam should be designed to prove the ROBOCUT melt ejection principle. Further studies of the ROBOCUT technology will determine the final beam patterns and their effectiveness.

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Food Customization: An Analysis of Product Configurators in the Food Industry

Monika Kolb, Paul Blazek and Clarissa Streichsbier

Abstract Product customization offerings appear in a growing number of industries (Configurator Database, cyLEDGE Media GmbH, www.configurator-database.com, 1). When looking at the customization potential of food, customer preferences in terms of taste tend to diverge a lot. In addition, there are different needs like nutrition and health which lead to a more heterogeneous diet. These factors enable a perfect playground for the concept of mass customization. Eighty-eight existing online food configurators, which are listed in the Configurator Database, have been identified and analyzed. The objective of this paper is to provide the status quo of the food and beverages industry in the market of mass customization. The results shall show insights and implications for creating a food customization project.

Keywords Mass customization · Food customization · Product configurators

1 Introduction

The increasing awareness of the needs of the customer at the level of individuality, the low costs of information technology, and the development of technology are drivers of the trend toward individualization and customization [2]. The term mass customization derives from the combination of the two apparently contradictory

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terms 'mass production' and 'customization.' The aim of mass customization is to tailor make products for individual customers at costs comparable to mass production [3].

The interaction with the customer through a configurator is the core business of mass customization [3]. Interaction processes with customers include both the incorporation of customer requirements and the specification of product properties by the customer. The design of the product properties is realized by using a Web-based configurator [4]. Walcher and Piller [5] identified parameters that have a strong influence on the perceived quality of such a configurator: visual realism (i.e., how realistic is the visualization of the configured product), creativity (i.e., the degree of creational freedom during the configuration process), enjoyment (i.e., the degree of fun, delight, and entertainment of the configuration process), and choice options (i.e., the provided choice options in the configuration process).

The Configurator Database powered by cyLEDGE [1, 6] is a collection of existing Web-based product configurators. The database was started in 2007, and since then, the collected data have changed a lot as the market of individualization and personalization is very fast moving. Many new configurators have been launched, especially in the field of food customization. The database currently contains more than 900 product configurators which are categorized in 16 different industries. Within these, the food industry is the third largest, after apparel and house & garden.

2 Characteristics of Food Customization

Food customization is one of the fastest developing industries in the field of mass customization. Within this industry, the variety of products is wide-ranging, from customizable tea to popcorn and sausages [6]. Nevertheless, according to Matthews et al. [7], mass customization is still rarely applied by companies in the food industry. This lack of food configurators can be traced back to several reasons. Food products need to be processed and distributed quickly, entail complex handling requirements, and are produced under demanding legal provisions. These are key factors that limit the ability to customize food products. Nevertheless, there are some food categories which are suitable for mass customization, especially those which are non-perishable. Moreover, the packaging or labeling of a food product is perfectly applicable for individualization.

Yeretzian et al. [2] have identified two driving forces to customized food. First, there is a rising awareness among consumers that individuals are different concerning nutritional needs. Consumers are increasingly looking for foods customized to their specific nutritional requirements. Accordingly, the demand of individualized food derives especially from the recognition that inadequate dietary choices impede our well-being. The second driver of the high demand of customized food is the individual flavor preferences, which influence choices of every consumer. Food is a commodity that appeases hunger, but more importantly, it is a source of enjoyment. Flavor serves as a criterion in making food choices. Even the most nutritious food will not be regularly consumed if its taste does not fit to the consumer's preferences.

Insel et al. [8] differentiate hedonic food which people consume because of taste and smell, enjoyment and lifestyle and functional food, which provides health benefits. Requirements regarding both hedonic issues and health issues are very heterogeneous and require concepts which allow the creation of individual nutrition [9]. Mass customization enables creating a unique food or beverage that exactly matches the individual needs of each consumer. By offering a Web-based product configurator, a mass customizer allows its customers to individualize a product appropriate to their needs.

3 Measures and Evaluations

The aim of the following analysis is to investigate 88 food configurators (see appendix) listed in the configurator database [1, 6]. The brands behind the 88 configurators are located in 7 different countries. The majority is based in Germany (54 brands) and the United States (28 brands). Every configurator was analyzed based on the following predefined criteria [3, 5, 10, 11]:

- Product: Which kind of product is offered for customization
- Level of customization: What can be individualized
- Steps in configuration process: How many steps has the consumer to fulfill
- Visualization: How is the product depicted
- Tutorial: Is there a tutorial which explains the usage process of the configurator
- Support: How is the customer supported during the process
- Social Media: Which social media channels and interaction possibilities are used.

3.1 Product

The analysis indicates that the currently most offered products in food customization are 'chocolate' and 'sweets and candy,' followed by 'cereals' and 'cakes.' Configurators of these product categories offer a variety of different ingredients and exotic flavors which customers usually not get offered as a regular product. Every user can assemble a unique composition. Besides these popular product types, there are also rather unusual customizable products like spices, popcorn, or ketchup (Fig. 1).

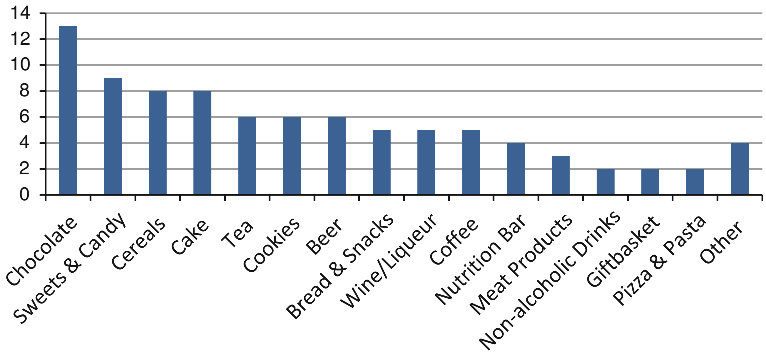
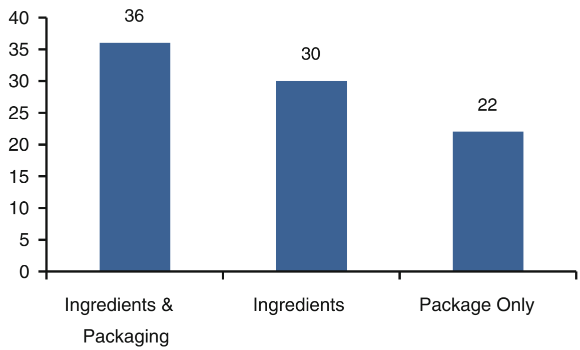


Fig. 1 Product configurators in the food industry ($n = 88$)

Fig. 2 Level of customization ($n = 88$)



3.2 *Level of Customization*

In the field of food customization, there can be made a general distinction between the customization of the ingredients (functional customization) and the personalization of the food′s packaging (cosmetic customization) [11]. In the first case, the individual liking of each customer is determinative. Taste and preferred flavors differ strongly, and therefore, customers appreciate the possibility to create their own assortment. The own design of the packaging on the other hand is often used for personal presents as it gives every product a unique appearance.

Our investigation reveals that 36 out of 88 food configurators provide both, customization of ingredients and packaging. Thirty concentrate on the individualization of ingredients and flavors, and 22 provide the design or personalization of packaging only (Fig. 2).

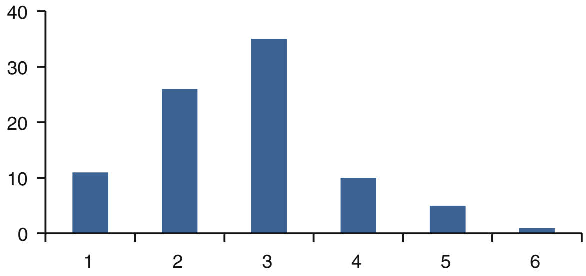


Fig. 3 Number of steps in the configuration process ($n = 88$)

3.3 Steps in Configuration Process

A configuration process always consists of various steps a user has to pass through in order to get his individual product. Every task may be represented in an own configuration step. However, the user should never be overchallenged by too many single steps.

The results show that most configuration processes are separated in two or three steps. Some configurators even consist of five or six steps which tend to be more appropriate for highly complex products such as cars or computers (Fig. 3).

3.4 Visualization

The type of visualization describes the illustration of the configured product or the contained ingredients. Reichwald and Piller [11] state that a realistic image of the product is one of the most vital parts of a configuration tool. The visualization replaces the physical product. It should on the one hand support the customer in making decisions and on the other hand stimulate his creativity. In food customization, the taste is more important than the visual appearance of the product, but due to the fact that flavor cannot be showed online, an attractive visualization affects the customers' buying decision. Moreover, a realistic image of the product is especially important when it comes to the personalization of packaging or labels.

Four general types of visualization can be distinguished:

- 3D photorealistic
- 2D photorealistic
- 3D illustrated
- 2D illustrated.

The evaluation of the visualization types shows that more than half of all configurators use visualizations in 3D photorealistic. The other 3 types are less used in the food section (Fig. 4).

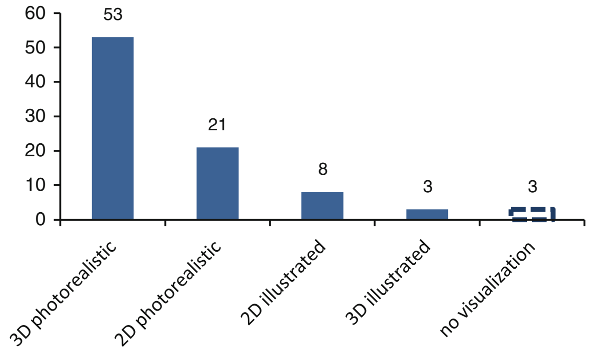


Fig. 4 Usage of visualization types ($n = 88$)

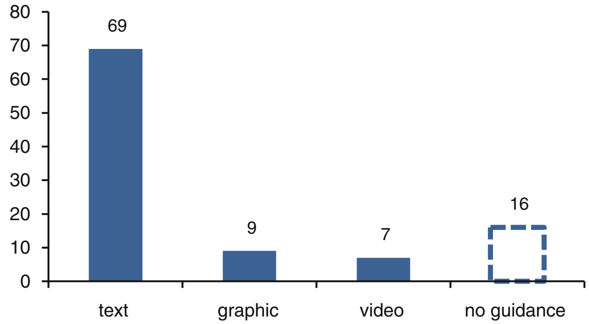


Fig. 5 Usage of tutorials ($n = 88$); multiple options possible

3.5 Tutorial

Offering different options to the customer leads to a certain degree of complexity. To compensate this complexity, a configurator should include a tutorial that provides an explanation of the process and the configuration steps [3]. Such a tutorial can be executed in various ways. This analysis differentiates text tutorials, graphic tutorials, and video tutorials.

The text tutorial is by far the most used form of tutorial. Sixty-nine of all analyzed configurators provide their users with this form. Graphic and video tutorials are offered rarely, and 16 companies do not explain the configuration process at all (Fig. 5).

3.6 Support

Besides tutorials, there are other ways to support the user in case of questions or misunderstandings. Providing customers with one or more channels where their questions are answered helps to understand the configuration process and eliminate

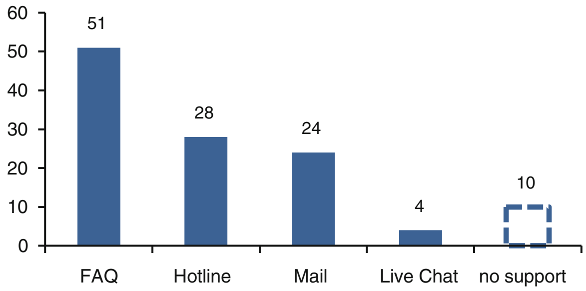


Fig. 6 Usage of support channels ($n = 88$); multiple options possible

problems [3]. In this study, the usage of live chat, hotline, mail support, and FAQ is evaluated.

The evaluation indicates that a lot of companies offer at least one of the four support options. The most used type of support is FAQ. Twenty-eight companies offer a hotline for customers, and 24 companies give support via mail. The live chat support is a recent trend that is used for more and more online shops to guarantee a real-time assistance. Only 4 out of 88 analyzed food configurators use this type of support. Ten companies sell customized products without any support (Fig. 6).

3.7 *Social Media*

As social media is getting a part of many customers' and companies' communication, it is necessary for mass customizers to deal with these channels for interacting with the user [10]. Social media provides a wide range of potentials which mass customizer can use. Facebook & Co can be used to reduce the uncertainty about the performance of the user's own design. Via social media, users can share self-designed products with other users and get feedback. In addition, users can be inspired by the designs published by others [12].

This paper focuses on the two most popular platforms Twitter (www.twitter.com) and Facebook (www.facebook.com) as well as the usage of sharing possibilities.

3.7.1 Facebook

Companies doing food customization are very advanced in using the social network. Seventy-five of all analyzed companies offering a food configurator have a Facebook fan page. The intensity of usage differs strongly, which can be monitored by the number of fans. The company with the most fans on Facebook is 'Hershey's' with about 5.8 million fans, followed by 'Jones Soda' and 'mySwissChocolate.' However, there are also brand fan pages with less than 10 fans, which indicate that Facebook is not or barely used by them (Fig. 7).

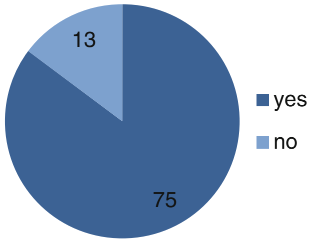


Fig. 7 Facebook usage among food configurators ($n = 88$)

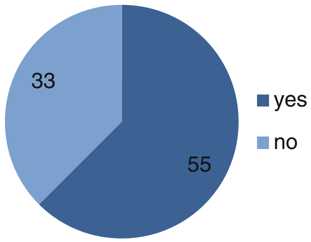


Fig. 8 Twitter usage among food configurators ($n = 88$)

3.7.2 Twitter

Twitter can be an additional marketing or service channel for mass customizers. Nevertheless, it is not as common as Facebook. Fifty-five of all analyzed food Web sites with an integrated configurator use Twitter for interacting with customers and prospects. The most followers can be found in the 'mymuesli' Twitter account with about 14.000 followers, followed by 'element bars' and 'Jones Soda' (Fig. 8)

3.7.3 Sharing Possibilities

The possibility of sharing content from a Web site to different social media platforms has become very popular. Customers can easily share the Web site, product, or creation with their social network and thus increase the reach or the traffic on the company′s Web site. Social sharing mechanism can help users to get feedback or show their created product to their social network. There is a variety of sharing possibilities available. The research has investigated the sharing options Facebook Like, Facebook Share and Facebook Send, Tweet, Google Plus share, Pin it, and the sharing via mail.

Half of the analyzed companies offer the possibility of sharing their content via social media. The most popular possibility among food configurators is the Facebook Like button with 27 utilizations. Customers can easily state that they like the company by just clicking one button. Sixteen companies provide a Tweet button. The other options are not very common until now but may gain importance in the future (Fig. 9).

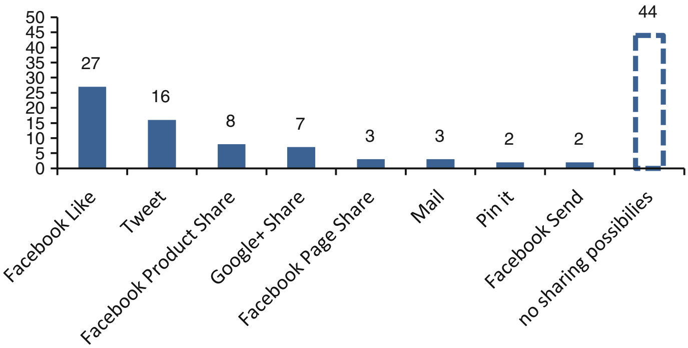


Fig. 9 Social media content-sharing icons ($n = 88$); multiple options possible

4 Conclusion

Food customization is a contemporary way to satisfy the heterogeneous needs of nowadays consumers. Food customization is feasible for many different kinds of food and enhances the value of the product. According to the analyzed 88 Web-based food configurators, the following implications for creating a food configurator can be stated:

- As food products are often used and marketed as a present, the option of customizing the packaging is recommended.
- The configuration process may be separated in two or three steps which reflect the necessary customization tasks.
- A photorealistic visualization of the single-product components is necessary to whet the appetite for the food product. Various views of the assembled product may raise the customer's imagination and the likelihood of a transaction.
- It is necessary to convey the feeling that there is help offered when configuring an own product, regardless of whether form of tutorial or support is used.
- The configuration process and the associated social interaction possibilities may contribute to the customer′s satisfaction with the product and thus strengthen the customer's identification with the company.
- The possibility of sharing the individual creation of the customer via Facebook and Twitter represents a great potential to connect users and spread the idea of customized food.

Appendix

See Table 1

Table 1 URLs of the 88 analyzed food configurators, listed in the Configurator Database [1]

www.allmytea.de	www.meinewunschpraline.de
www.bakedbymelissa.com	www.meinkaffee.de
www.barrelsandbottles.co.uk	www.meinriegel.de
www.beerstickr.com	www.memarmelade.de
www.blendsforfriends.com	www.miximuesli.de
www.braufabrik.de	www.mojamix.com
www.brewtopia.com.au	www.muesli4ever.de
www.wrappedhersheys.com	www.muesli4me.com.au
www.cereal-club.de	www.müsli.de
www.champdeluxe.com	www.memarmelade.de
www.chocolissimo.de	www.muesliandmore.com
www.choccreate.com	www.mybeans.com
www.chocolato.de	www.my-choc.com
www.chocomize.com	www.myheinz.com
www.chocri.de	www.myjellybelly.com
www.cocoabella.com	www.myjones.com
www.cookie-mania.de	www.mymms.com
www.customwinesource.com	www.mymuesli.com
www.deinbonbon.de	www.my-pizza.at
www.dein-eigener-wein.de	www.mysaftbar.de
www.deinetorte.de	www.mystarbuckssignature.com
www.deinsekt.de	www.myswisschocolate.ch
www.derteebaukasten.de	www.myteamix.de
www.der-zuckerbaecker.de	www.naschplatz.de
www.designatea.com	www.paduno-kaffeepads.de
www.ecreamery.com	www.pastarie.com
www.elementbars.com	www.personalwine.com
www.elicheesecake.com	www.persoenliche-schokolade.de
www.fergusonplarre.com.au	www.popcorner.at
www.gemischte-tuete.com	www.proteinmixer.com
www.gumdropcookieshop.com	www.scake.com
www.designyourheineken.nl	www.schokokreationen.de
www.hersheysstore.com	www.simplyscrumptous.com
www.ibonbon.de	www.slantshackjerky.com
www.ichbackdich.de	www.snackselect.de
www.idbeer.de	www.sonntagmorgen.com
www.jlhufford.com	www.spoleto.com.br
www.jonessoda.com	www.spreewald-praesente.de
www.kekswerkstatt.de	www.subway-sandwiches.de
www.kern-energie.com	www.worldofsweets.de
www.krassola.de	www.wunschcurry.de
www.kuchenkurier.de	www.wunschkeks.de
www.meinebackstube.de	www.wurstmixx.de
www.meine-mettwurst.de	www.youbars.com

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Generative Design Approach for Modelling of Large Design Spaces

Bastian Sauthoff and Roland Lachmayer

Abstract Mass customisation of mechanical and mechatronic products requires computer-aided configuration tools including parametric models of the product. For an extended individual adaption, approaches including iterative configuration processes are necessary. Knowledge-based engineering systems (KBES) are developed for this kind of customisation tasks among other things, but they are still not universally applicable and accepted in the industry. Thus, in this paper, an approach for the modelling of large design spaces by parametric models is presented. This approach implies a confinement of the widely defined pretension of KBES by a systematic modelling of practical conversant design solutions. In contrast to the modelling of higher-level design rules, the exclusion of inexpedient variants is completely possible. The detailed aspects of the approach consisting of a structural design, effective areas and design elements are illustrated in this paper as well as methodological aspects. The application is demonstrated by a wheel carrier design.

Keywords Product modelling · Parametric design · Design optimisation · Knowledge-based engineering · Modelling principles

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1 Introduction

For mass customisation of mechanical and mechatronic products, computer-aided configuration tools are common used in the industry. Based on a static and a customer-dependent set of functional and geometrical parameters, the final design of a product is configured. The precondition for the development of such kind of configuration tool is an explicit relationship between function and design. While the approaches of size ranges and assembly design kits, e.g., the methodology of Pahl et al. [1], are predicated on this aspect, extended configuration demands and iterative adaption process. This aspect is illustrated in Fig. 1.

Every product is defined by a set of parameters subdivided in geometrical and physical ones. A fraction of this parameter set is accounted for configuration. The functional design is generally modelled by interrelationships of parameters. If a set of explicit constraints is deducible from the interrelationship including all configurable parameters, a direct configuration is feasible. Whenever an explicit constraint set cannot be defined, an iterative configuration process has to be established. In this case, the well-adapted parameter configuration cannot be calculated directly. An evaluation of a specific parameter set by an analysis model combined with an iterative parameter variation is the only feasible way. Particularly for the configuration of components dimensioned by physical field problems, an iterative configuration is essential. Thus, an iterative configuration is obviously much more complex that a direct configuration, but the feasibility of configuration is more flexible as well.

To support mass customisation based on iterative configuration models, knowledge-based engineering systems (KBES) have been developed since the 1980s. The exploration of large parts of the design space as well as the automatisation of repetitive design tasks is still the visions of this research field. But the complexity in reference to development and implementation as well as the integration in company working processes restrains the application today as well [2, 3].

1.1 Challenges of Extended Configuration

To confine the approaches of KBE in consideration of application for mass customisation, the today's challenges of this field are summarised.

1.1.1 Effort of Development

Normally the product design grows up continually during the design process. Thus a KBE-based configuration systems must include the steps of the underlying design synthesis. The design steps have to be transformed into rules including

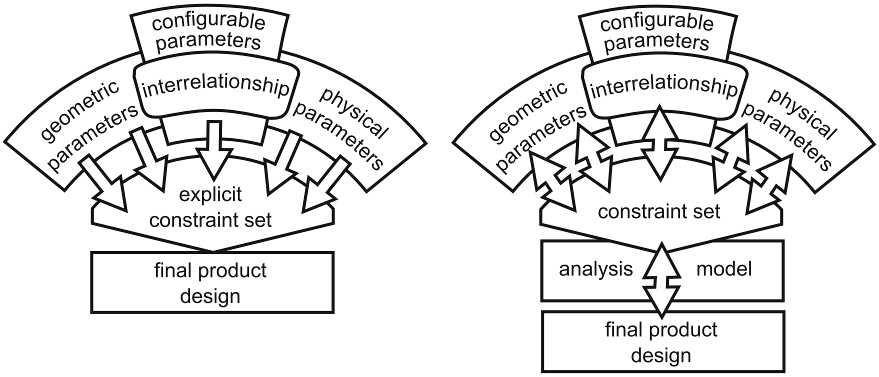

Fig. 1 Direct and iterative configuration

functional as well as geometrical aspects on an abstract level. This way of engineering fundamentally differs from the iterative and creative way of engineering work. Additionally, the development of such a meta-model efforts a lot of engineering resources which can only be applied by big companies. Thus, major challenges relating to configuration tools in almost the same manner are an improvement of accessibility by engineers and methodology for applicable development [2].

1.1.2 Implementation and Interaction with Existing Tools

A lot of scientific articles can be found about specific implementations of KBES characterised by specific programming languages to build a configuration system. Until now a lot of CAD tools are quite familiar with parametric modelling and direct configuration features. But tools for a development of iterative configuration tools often require deeper understanding of programming. Additionally, the programming and connecting interfaces, especially between tools of different companies, are difficult to manage. Thus, implementation of iterative configuration tools in existing development tools as well as existing work flows without isolated application is quite a challenge [3, 4].

1.1.3 Integration of Product-Specific Knowledge and Design Rules

Analysing guidelines for engineering design, there are two different kinds: On the one hand, general design rules are describing engineering knowledge which is related to a specific manufacturing technology of principles of mechanics. These rules are important for the design work of engineers, but a transformation into constraint-based rules of a KBES is quite difficult. One reason for this aspect is the independent formulation of product-specific geometrical design. On the other hand, there are a lot of product- and company-specific design rules based on engineering experience, simulation, or testing. These are often closely solution oriented and not commonly available. Because of this aspect, an integration in a configuration system is only possible if the design space is very close to the application range of these rules. Thus, the formulation of design rules on an applicable but also product-variant-space level is still a challenge [1, 5, 6].

1.1.4 Exclusion of Inexpedient Variants While Modelling a Large Design Space

Exploring the design space of variants for a defined configuration parameter set the ratio of theoretical available, but inapplicable design solutions is important for the configuration effort. Particularly this aspect is weightily if the design space increases. Thus, a modelling of the complete design space is often inefficient. A defined restriction of the design space to the sections where feasible solutions are expected is quite a challenge.

Summarised a confinement of the approaches for KBE with focus to mass customisation is a necessity to make the grade of these challenges. In particular, available geometric-related design solutions have to be brought in focus instead of an overlaying meta-model describing design activities in general.

2 Parametric Modelling Approach

Based on this perception, an approach is developed focusing the exploration of large design spaces by well-known design concepts.

2.1 Levels of Design Impact

For identification of a feasible level of abstraction of a product design, the different levels of design impact are analysed. In Fig. 2, the levels of design activities related to the development steps are illustrated. The iterative design process is often affected by the following developing strategy: Planning activities as well as first conceptional developments are made on general product level. During the ongoing design process, the activities are further more focused to component design and eventually to component section details. Thus, the impact of design switches into detail. But the final product design is defined by an iterative reflection of the design increasing the point of view to the product level [7].

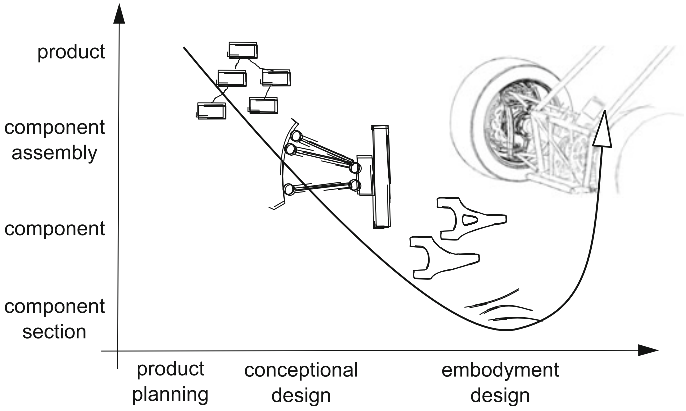

Fig. 2 Levels of design impact instancing a wheel suspension

For mass customisation using KBE-based tool, this aspect clarifies the problem of modelling underlying design activities. Both directions of abstraction have to be integrated.

2.2 Modelling Approach

Because of mentioned aspects, it is a reasonable way to develop an approach which is strongly related to the design of a product itself. For this purpose, different methodology approaches of embodiment design are analysed. The design methodology of Roth [8] is identified as a very strictly structured approach nearby the geometric forming of design. Roth subdivides the process of embodiment design in the steps of structural design and contour design. The inherent structure of component or component assembly is designed using structural design. Based on this minimal-function-oriented skeleton, the contour is defined. During both steps, an iterative process of shape variation is done to identify the best design. The interaction of components is modelled by effective areas. The basis of all steps and operations is scalable representation of the product.

Based on this approach, it is recommended to apply this way of geometric oriented design for the development of computer-aided configuration models. Because of the issue that a defined component-oriented structure with effective areas to link the structure elements limits the variation part boundaries, the approach is expanded to a design-characteristic-oriented structural design. This implies that effective areas are not solely located at the boundary of parts. Based on this a product is represented by inherent sections of structural elements coupled by effective areas. For the variation in the final shape, so-called design elements are defined which are related to a special constellation of structure and effective areas. Thereby, the topology as well as the contour design of an design element

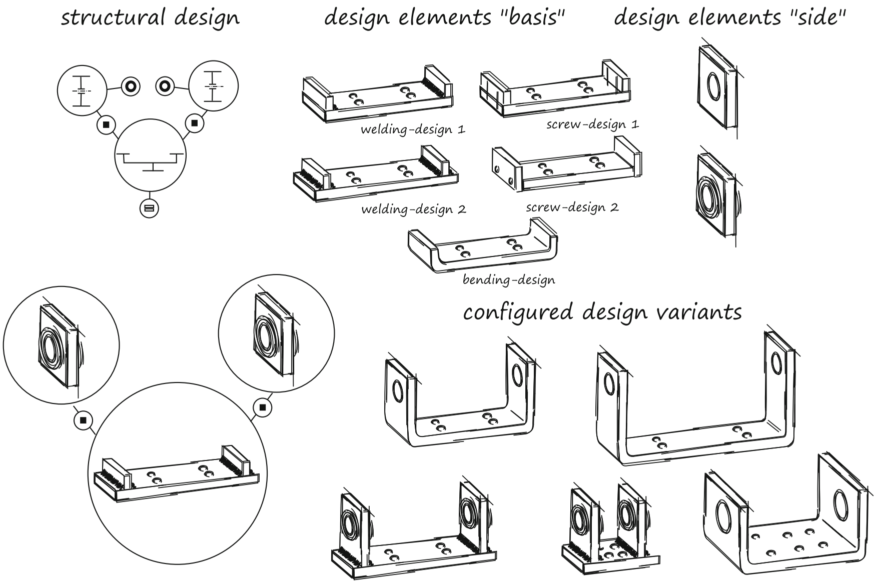

Fig. 3 Modelling approach instancing a mount

can vary completely while retaining the inherent structure. In Fig. 3, the approach is illustrated by a mount. The inherent structural design of a mount consists of a base element with one effective area for linking to a further component and two internal effective areas for linking to design elements of the side class. The side class elements are identified as characteristically equal. They have an external effective area for circular formed components. For the design elements of the basis class as well as the side class, different design variants are developed considering several design rules and manufacturing technologies. Based on the parameters of the structural design and the effective area design, the elements are assembled to different design variants.

2.3 Levels of Parametrisation

Going into detail different levels of parametrisation are identified. On the one hand, there are a few fundamental parameters on the level of structural design characterising the whole mount. On the other hand, there are special parameters characterising the individual design of the effective areas subordinated by the design element shape. Thus, the parametrisation is classified by these three levels. In Fig. 4, the two levels of structural and effective area design are illustrated for the mount. On the level of structural design, the length and the height are the fundamental parameters. Additionally, the positions of the effective areas related

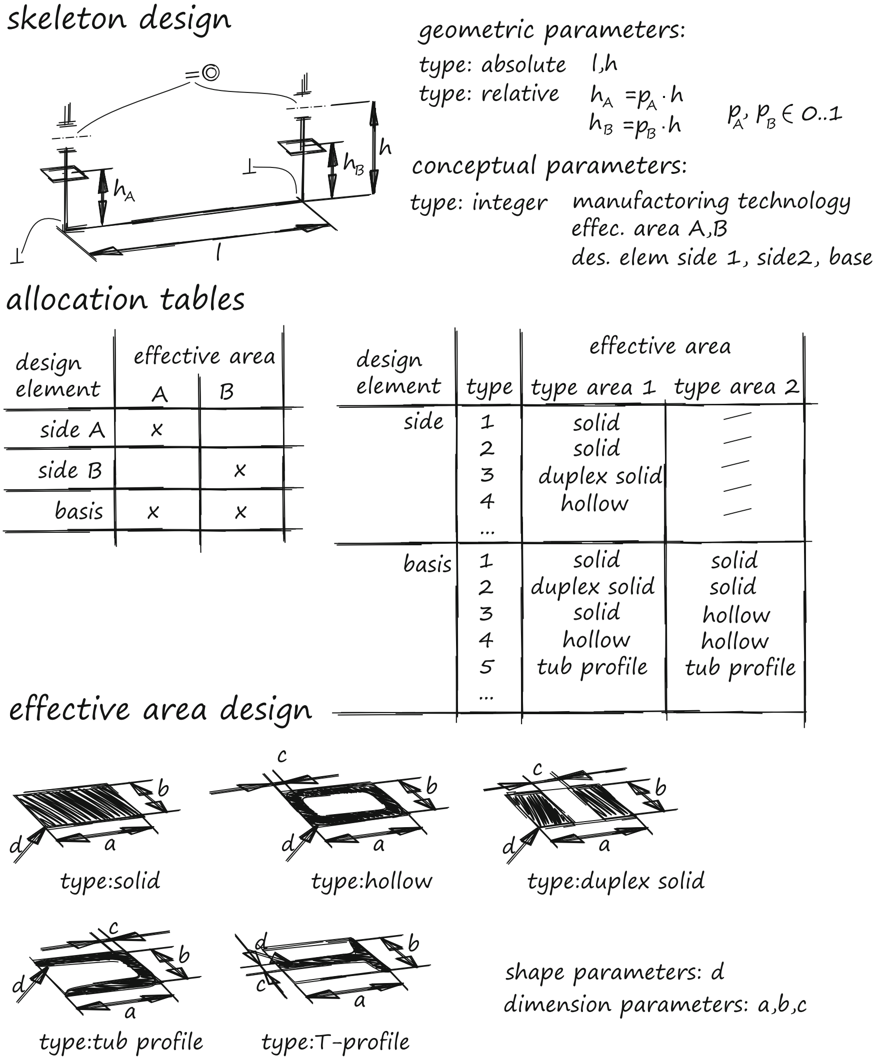

Fig. 4 Design of skeleton and effective areas

to the skeleton design are parameterised to complete the geometric model. They are, different from length and height, defined as relative proportion parameters supporting the variation independence. To control the substitution of effective areas and design elements, there are additional conceptional parameters on the level of structural design allocating the variants by integer parameters. Furthermore, a parameter for the manufacturing technology is defined which constrains unfeasible combinations of design elements assigned to different manufacturing technologies. Additionally, constraints for the combination of design elements and effective areas are necessary because the type of an effective area is fundamentally important for the shape and topology of the design elements. Thus, allocation tables are introduced to classify the design elements by including effective areas and the design element classes by effective area design. Thereby, the design space is restricted to feasible design solutions. The allocation tables are established on the level of structural design, too.

The effective area designs of the mount, illustrated in Fig. 4, are parameterised by a shared set of parameters. These parameters are interpreted individually by every type of effective area. Width (a) and length (b) of the area designs are identified as characteristic dimensions completed by a parameter for the inner proportion (d). While width and length are nearly identical interpreted by every area the parameter c, defined by a fraction of width or length, has fundamentally different influence to the different area designs. Nevertheless, a value variation in c in the range of 0.1 is accomplishable without the risk to generate unfeasible design variants. Thus, this generative approach demonstrates a combination of a large design space and the confinement of feasible solutions. The parametrisation of design elements is implemented by the same strategy.

3 Modelling Principles for Generative Design Approach

Based on experience in modelling different types of design elements according to the above approach, general modelling principles are formulated in order to support its application.

Modelling principle 1 *Level of parametrisation: The impact of a parameter variation should be confined only to one level of structural design, effective area design or to a type of design elements. The impact should be as local as possible.*

Modelling principle 2 *Complexity of design elements: For topology variations, the definition of additional design elements is advisable, while contour variations are feasible modelled by one design element as long as the order of the contour design does not change.*

Modelling principle 3 *Coupling of parameters: Coupling of parameters in the space of one level should be avoided. Coupling of parameters over different levels is preferred.*

Modelling principle 4 *Parameter properties: For a stable regeneration of the design model, parameters should be coupled by fractions of other parameters in a specified range.*

Modelling principle 5 *Parameter hierarchy: The level of structural design should be dominated by a small number of parameters. The number of parameters of the effective areas as well as the design elements should be decreased to a suitable level by linking similar parameters. Example: The curving of different* *edges should be described by one parameter as long as a curving does not fundamentally characterise the design element.*

Modelling principle 6 *Design rules: Design rules should be applied to each effective area design as well as to each design element individually. The definition should be as independent as possible from the value range of parameters.*

Modelling principle 7 *Choice of CAD elements: The used CAD elements like lines and arcs to model the design elements should be as simple as possible to support a robust parametrisation. In particular, higher-order elements like splines are dependent on several dependent parameters. For example, the modelling of a curved contour by one line and two arcs instead of a spline limits the design space but improves the parametrisation.*

To demonstrate the application of the approach, the design space of a race car wheel carrier is exemplified. The impact for application is the scope of individual adaption of the wheel carrier to its load cases [9].

4 Application Example: Wheel Carrier

A wheel carrier of a race car (Fig. 5) consists of a segment for the wheel bearings and three application points for the steering tie rod and the suspension arms linking the wheel to the body. Directing the wheel forces to the application points is the main function. Thus, the design of the wheel carrier is significant for its durability as well as its weight and manufacturing costs. The structure of the carrier is analysed, and three inherent types of design elements are identified: The bearing element which includes the wheel bearings, three connector elements linking application points and bearing element and three application point elements including the connection to the arms and the rod. Although the connector elements as well as the application point elements differ in their local occurrence, they are merged in one element class for every element type. The effective areas between bearing element and connector elements are identified as cylindrical faces, the other effective areas are plains with different contour types. The skeleton for the parametrisation of the structural design mainly consists of effective area positioning parameters. The distance between the application points and the bearings is inherent parameters for the wheel carrier, too. In Fig. 5, exemplary a choice of connector design elements is presented. Although there are different manufacturing variants (casting, welding, and cutting), every instance is modelled by an identical parameter set. The determining parameters for these elements are the wall thickness, edge rounding, and properties of the right and left contour.

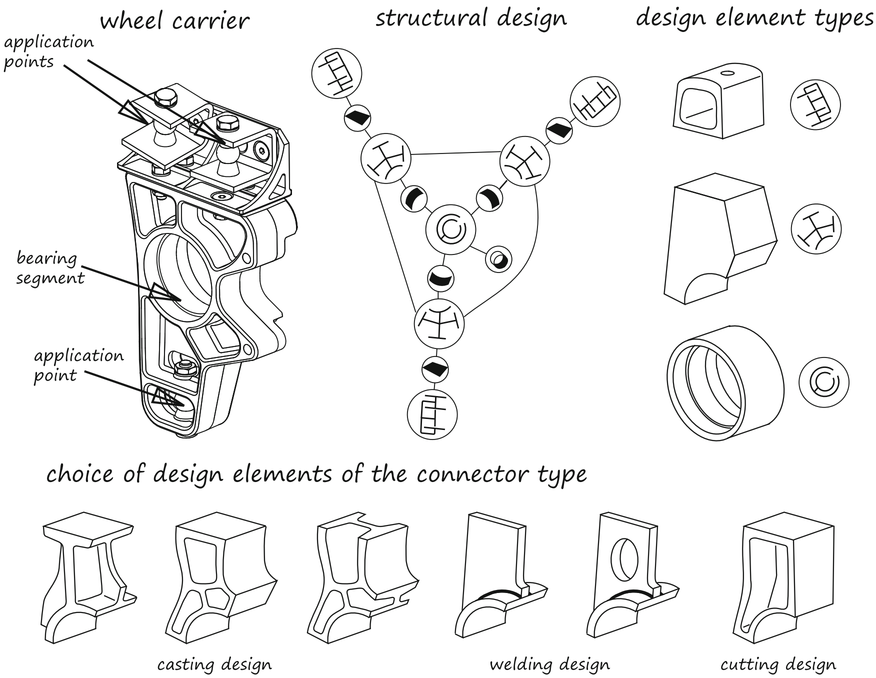

Fig. 5 Generative design model of a wheel carrier

4.1 Design Adaption by Optimisation Algorithm

The optimal design of the wheel carrier is calculated by an optimisation algorithm based on an objective function including the mechanical stress distribution, the manufacturing costs as well as the weight of the carrier. Modelling the design space of the wheel carrier by the presented modelling approach, all design variants can be generated by parameter variations. Thus, optimisation by a genetic algorithm is a feasible way although the design model includes topology design changes. For the implementation of the generative design approach, a computer-aided design tool which support parametric design in parts and assemblies is necessary. Additionally, the tool has to provide an application programming interface to implement the allocation tables controlling the variation process of effective areas and design elements. Based on these features, an optimisation can be done manually. For the adaption by a genetic algorithm, the implementation of an interface to a finite element environment as well as an external genetic algorithm is implemented [10]. This requires definitely some effort but is a more feasible option than developing an standalone knowledge-based engineering system.

5 Conclusions

The presented generative design approach supports direct as well as iterative configuration as a tool of mass customisation. The design space is confined by systematic analysis of structure and shape. On the one hand, feasible solutions are favoured, and on the other hand, this way of modelling limits the number of solutions in general. No higher-order design rules are formulated whereby the complicity is reduced. The integration of all design rules in the design elements does not require such a formulation. Relating to mass customisation, this approach supports the computational modelling of individual product variants focusing embodiment design. In comparison with common KBE applications, creativity and the iterative design exploration characterising the way of engineering work are not decreased. But for an implementation of an optimisation process, programming effort is still required. Outlining further challenges, an extension to assembly design introducing part overall effective areas is necessary. Further there is the question of the number of design elements necessary to model a product optimally.

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How to Squeeze a Configurator into a Handheld Device

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Abstract In this paper, it is presented the implementation of a solar-powered pumping system configurator based on a new approach for the modelling of the configuration process of product families. An important outcome of this approach is that if a few modelling conditions are satisfied, deriving product family members becomes a direct (backtrack-free) process. Consequently, a configuration problem-solving process that typically would require a high-performance computer can be squeezed into handheld devices as a standalone program.

Keywords Product family · Product configurator · Backtrack-free search · Solar-powered pumping system

1 Introduction

Solar-powered pumping systems (SPPS) have long become a viable economic option for rural areas and the widespread of this technological solution will have a great socioeconomic impact in many countries. Nevertheless, this is still a largely unexplored market segment which will require the increasing involvement of the private sector [1]. For a company interested in this market, sending trained technicians to distant sites in the countryside to visit potential customers is a costly

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approach, not to mention the shortage of trained technicians in SPPS. A better approach is to provide an established sales force with an SPPS configurator that can be run as standalone programs on devices such as smartphones and tablets. This strategy is justified by the fact that the sales force would require little training and make use of devices that are becoming very popular as tools to configure the SPPS. Moreover, these tools can be used in places where there is no Internet connection (typical of rural areas in developing countries), which renders a centralized configuration server useless. However, it is well known that product configuration tends to be a time-consuming process that requires high-performance computers. Hence, one might wonder, how is that a handheld device can be used for this role?

In this paper, we apply a new approach to model the configuration of product families to the SPPS problem. This approach is based on a knowledge framework which combines a generic product structure (GPS) and a constraint network extended with design function (CN-F) model to represent product families. One important outcome of this approach is that, if a few modelling conditions are satisfied by the CN-F model, deriving product family members becomes a direct (backtrack-free) process. To show the applicability of our approach to the SPPS problem, we implemented a configurator which is capable of quite challenging solutions. The configurator was also tested on an emulator for mobile devices to demonstrate the viability of running it as a standalone program on a handheld device.

In what follows we will first make a brief review of related works. Then, we will apply our modelling approach to represent an SPPS product family and define the method for deriving its members. After that, we will present our implementation of the SPPS configurator. Finally, we make some concluding remarks.

2 Related Works

Constraint network (CN) has been a successful approach to deal with configuration problems [2]. However, since its proposal [3], various extensions to the classical CN model have been introduced to cope with the specificities of product configuration problems [4]. Typically, backtrack algorithms are used to find solutions for configuration problems, which tends to be a time-consuming process. To overcome the inefficiency of the search method, knowledge from the configuration domain has to be used to guide the search process [5]. On the other hand, it has been shown that under some conditions, depending on the topology of the CN model and its degree of consistency, finding solutions can be a backtrack-free process [6]. Other backtrack-free approaches rely in a pre-processing stage to map all the solutions in the design space prior to the configuration stage, when the actual problem-solving occurs [7]. Although the search for solutions is faster, these approaches cannot avoid the exponential grows of memory utilization in the pre-processing stage.

From the engineering perspective, graph grammar has been used as an approach for deriving members of product families [8]. A review on product families and methods for their design can be found in [9, 10], respectively.

3 The Solar-Powered Pumping Product Family

A typical SPPS is composed of a few components. At the core of the system, there is a photovoltaic (PV) array that provides power to a water pump. To improve the pump performance, a pump controller is used to condition the power and to control the pump. A float switch (S_T) is used to turn the pump off when the water tank is full, and another switch (S_W) is used to turn the pump off when the water level at the well is low, thus avoiding that it runs dry. The components of an SPPS are connected by wires to transmit power and control signals. The water is carried from the well to the tank through a piping system. A battery bank may be added to the system in case it is necessary to pump water at night or during heavily clouded days. The charging of the battery bank is carried out by a charge controller. However, selecting and configuring these components to meet the application requirements and to optimize the system performance is far from trivial and may involve a large solution space.

Our approach assumes that the product family has already been developed. However, the framework with the GPS and CN-F models will capture all the relevant knowledge about the product family to define precisely its solution space and to set up the process to derive its members.

3.1 The Generic Product Structure

The GPS is a modular architecture composed of component types, which stands for classes of components. In our approach, component types belong to four possible categories: common/generic, optional/generic, common/specific and optional/specific. We say that a GPS represents the architecture of a given product family if and only if the architecture of each member of that family is isomorphic to a substructure of the GPS.

Figure 1 shows the GPS for our SPPS product family. The PV array, pump, controller, sensors, wiring and piping are considered to be common component types, i.e. they are present in every member of the SPPS product family. Otherwise, the battery bank and charge controller are optional component types. The well and tank sensors will be taken as specific component types, i.e. they do not vary among applications. Otherwise, all the other components are of the generic type, i.e. they will vary among applications and have two or more variants. It should be noted that, according to our classification, to be a common component type in the product family architecture does not imply that it is fixed. Actually, in

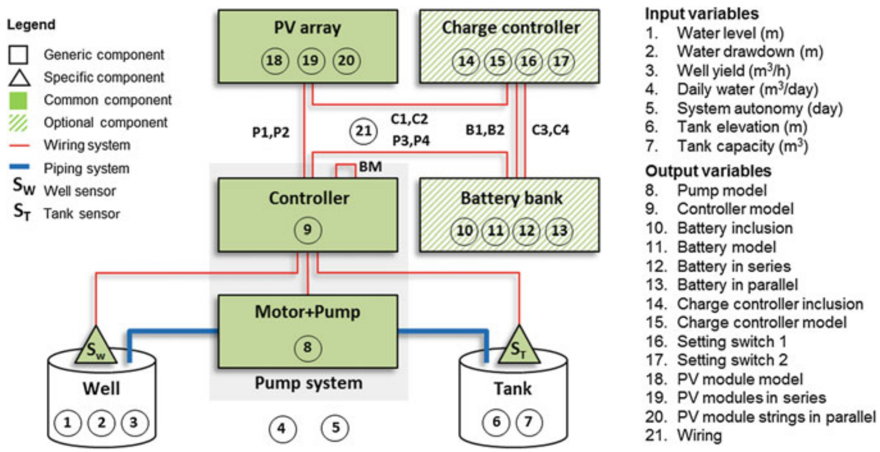

Fig. 1 GPS of the SPPS product family and the associated variable points

our example, most of the product family variability happens on the common part of the GPS.

The GPS is a useful means to delimit the design space of a product family because it constrains the possible arrangement of the components. However, it is not enough to determine completely what the valid configurations are and, in particular, what specific configuration will meet the requirements of a given application. Therefore, in our approach, the GPS is combined with a constraint network model to restrict the design space further.

3.2 *The Constraint Network Extend with Design Functions*

The CN-F model used in our approach can be regarded as an extension of the traditional CN model. It is defined by the tuple $\langle V, C, F \rangle$, where V is a set of variables, C is a set of constraints, and F is a set of design functions (abbreviated as *d*-function), such that every variable in V has at least one *d*-function attached to it that generates its values. In this section, we will see how these elements apply to the SPPS product family and how they complement the GPS.

Variables. Optional components in a product family are one main source of variability. However, most of the diversity in a product family may be due to the variability of the generic components. For example, a pump manufacture may provide a large number of pumps options, each one designed to operate optimally within a narrow window of total dynamic head and flow rate. Pumps may also be based on different pumping principles to maximize either head or flow rate. Variations among the product family members can be identified by variables and localized on the components of the GPS, but the scope of a variable can vary widely. It may be related to one specific feature or to the component as a whole. The set of all the values that can be assigned to a variable is its domain of variation. For instance, the domain of the variable *Pump model* is defined by the set {HR-03, HR-03H, HR-04, HR-04H, HR-07, HR-14, HR-20, C-SJ5-8, C-SJ8-7}.

Since the variability of the product family is related to the generic or optional component types, only such components are associated with variables, and because these are the variables that specify the product family members, they are referred to as output variables. A special type of output variable is the inclusion variable associated with optional component types (e.g., *Battery inclusion*). These are binary variables that defines if the component is included or not in the derived product. However, variations will also be related to the application environment. For example, applications will vary in the amount of daily water needed, the water yield of the well, the capacity of the tank, if pumping is necessary when the sun is not shining, etc. These variables express the customer requirements and are referred to as input variables. Figure 1 shows the list of all the input and output variables for the SPPS example. However, input and output variables are not necessarily disjoint subsets of *V*, and besides these two classes, the set *V* may contain a subset of auxiliary variables (shown in Fig. 6), which are neither input nor output variables. For example, the variable *Total dynamic head* is defined in terms of input variables, and although it is an essential variable for the choice of the pump system, it is not used to specify directly any of the components in the GPS. Therefore, it is classified as an auxiliary variable.

Constraints. Constraints define how subsets of variables in *V* are related to each other, thus restricting the possible combinations of values that can be assigned to them simultaneously. For example, the following constraints describe how the auxiliary variable *Total dynamic head* is related to some other variables in *V*:

C7 *Total dynamic head* is equal to the sum of the *Water level*, *Water drawdown*, *Tank elevation* and the friction loss of the piping system

C8 *Total dynamic head* must be less or equal than the head of the pump system, defined by the combination of the *Pump model* and *Controller model*

To satisfy a constraint, the values assigned to the variables in the expression defining it must render the expression true. If an optional component will not be included, all constraints involving non-inclusion variables on that component can be disregarded. An assignment of values to all the variables in *V* such that no constraint in *C* is violated is said to be a solution to the CN-F model. The set of all solutions will be denoted by *S*. As we will argue below, solutions in *S* correspond to members of the product family.

Design Functions. *D*-functions have been introduced as an extension to the CN model to capture the necessary knowledge to generate the values for the variables in *V*. For example, Fig. 2 shows the specification of *d*-function F4, which generates the values for *Total dynamic head* (the dependent variable) as a function of *Water drawdown*, *Water level* and *Tank elevation* (the independent variables).

```
F4(Water drawdown, Water level, Tank elevation)
Begin
1. Geometrical head = Water drawdown + Water level +Tank elevation;
2. Friction Loss = 0.05 × Geometrical head;
3. Total dynamic head = Geometrical head + Friction Loss;
4. If Total dynamic head ≤ the head of the available pump systems
5.     Then I/O ("The configuration process will be aborted because there is no available pump
6.          system that can overcome the total dynamic head.");
7.          Abort configuration;
End
```

Fig. 2 Specification of the *d*-function F4 attached to the variable *Total dynamic head*

Actually, an important consequence of *d*-functions is the dependency relation that they establish between variables. Now, if the value generated by a *d*-function is to be consistent with the values of the variables it depends on, it must incorporate all the constraints involving these variables. We say that a *d*-function incorporates a constraint if and only if every combination of the values of the independent variables (for which the *d*-function is defined) and the value generated from them, satisfy the constraint. For example, from lines 1, 2 and 3, it can be verified that constraint C7 is incorporated by F4. However, in general, a *d*-function is not dependent on all the variables related to the variable it is attached. For example, although the variables defining the pump system are related to *Total dynamic head* by C8, F4 is not dependent on them. Note that, the condition introduced in line 4 is only used as part of the configuration control mechanism.

Input variables are attached with special *d*-functions that request the user to assign a value chosen from a delimited range of values, which may be generated dynamically. Hence, except possibly for the input variables, all variables in *V* will necessarily depend on some other variable due to the *d*-function attached to them, forming a network of dependencies on *V*.

If a set of variables is strongly coupled, they can be grouped together to form compound variable and the same *d*-function will generate the values for all them. This is the case for F12, which selects the pump system from a performance table which, for a given total dynamic head, correlates the output flux and the input power for optimal performance of the pump systems. Inclosing strongly coupled variables into the same *d*-function also prevents dependency loops between variables.

It is this capability of *d*-functions to establish acyclic network of dependencies over *V*, together with their capability to generate values that are locally consistent, that forms the basis for the backtrack-free configuration process in our approach.

Moreover, since only values generated by the *d*-functions are taken into account in the configuration process, the domain of a variable in the CN-F model is defined as the set of all values that can be generated by the *d*-functions attached to it. An important consequence of this definition is that the domains need not to be defined

Instantiation algorithm:
Begin
1. Following the order in F, remove the first f_x which is enabled
2. Generate a value to x using f_x and remove from F all design functions attached to x
3. If $F \neq \emptyset$
4. Then go to 1
5. Else go to End and return "Success"

End

Fig. 3 Control algorithm for finding solutions to the CN-F model

explicitly and can be either discrete or continuous. All these properties have been used in our SPPS example.

4 Deriving Product Family Members

Based on our knowledge framework for representing product families, the configuration process will be divided into two stages. First, a solution to the CN-F model is found from the values of the input variables. Second, this solution is used to transform the GPS into a specific model representing the desired product family member.

As mentioned in Sect. 2, approaches base on the CN model typically use a backtracking method to find solutions. Moreover, in general, those approaches will not guarantee that a solution can be found or if this will happen in a reasonable time. However, if the CN-F model satisfies the following modelling conditions: (1) There are no dependency loops between the variables, (2) each variable has only one *d*-function attached to it, (3) the *d*-functions are defined for every combination of values of variables they depend on, and (4) every constraint is incorporated by some *d*-function; then, it can be demonstrated that the control algorithm shown in Fig. 3 is enough to find a solution for every consistent input to the CN-F model. This result is still valid if we make condition 2 less restrictive by allowing more than one *d*-function to be attached to the same variable. However, to handle this general condition, it would be necessary to introduce the concept of instantiation patterns (something we will not do in this paper). Anyway, for the SPPS example, the more restrictive condition is sufficient.

As it can be verified, the control algorithm is a straightforward one and does not admit backtracking. *D*-functions in *F* may be organized in any order. A *d*-function is enabled when all the variables it depends on are assigned values. The algorithm will iterate at most as many times as the number of elements in *F*. The demonstration that the CN-F model of the SPPS product family satisfies each of the above modelling conditions and that the control algorithm always leads to a solution will not be given here for space reasons. However, some evidence is given in the next section.

The second stage of the configuration process consists in transforming the GPS into a specific product model based on the solution found in the first stage. To achieve this, initially we remove from the GPS the optional components that are not needed. This happens whenever the value of the inclusion variable associated with the optional component has a specific value, for instance, zero. Otherwise, the component is kept on the structure. After this cleaning process, the remaining generic components are substituted by specific ones, as defined by the values of the output variables on them assigned by the solution. The resulting model can be used for the assembly of the correspondent product family member. Moreover, this product will meet the application requirements that started the configuration process. Since both stages use direct methods, we can conclude that deriving members of the product family is a direct (backtrack-free) process.

If the product family has been properly modelled, then every solution in S corresponds to a product family member and, on the other hand, every member of the product family must correspond to a solution to the CN-F model. In this case, we can conclude that the set S of solutions to the CN-F model precisely defined the solution space of the product family, and every consistent set of requirements expressed by the input variables leads to a product family member.

5 Implementation of the SPPS Configurator

The SPPS configurator was conceived as a tool to support the sales force, requiring them to have only enough technical knowledge about SPPS to make some assessments at the customer site. Customer requirements may be entered all at once or requested interactively by the configurator. To avoid inconsistent inputs, the configurator performs some checks on the requirements and suggests appropriate actions to remove them. The output of the configurator is the instantiation of the product family GPS by specifying the components, theirs settings and arrangement.

The method for the modelling of the configuration process can be generalized into the following steps: (1) definition of the product family GPS; (2) identification of the variables; (3) definition of their constraints; and (4) specification of the d-functions. These steps have been followed in Sect. 3 for the development of the SPPS product family; thus, we will not discuss them further. However, it should be stressed that adjustments to the CN-F model may be necessary in view of the four conditions stated in Sect. 4. Notably, the options at the input variables must be restricted appropriately to prevent downstream functions to become undefined. The abort condition introduced in F4 is an extreme action that prevents the customer requirements to be outside the domain of definition of the d-function that selects the pump system. Actually, if that happens, it does not make sense to continue with the configuration process.

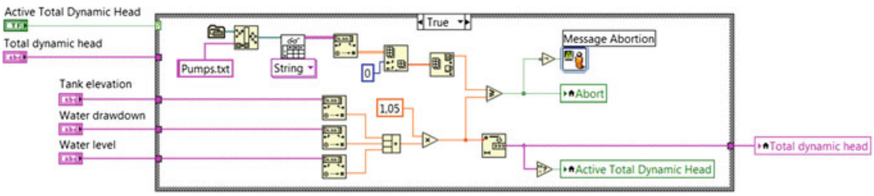

Fig. 4 Implementation of the *d*-function F4 in LabVIEW

Figure 4 shows the implementation of the *d*-function F4 (specified in Fig. 2) in the programing language LabVIEW. This is a relatively simple *d*-function. The most complex are the ones that define the arrangement of the battery bank and the PV array. The latter one, for example, calculates all possible arrangements for each PV module model available within certain limits of voltage and current and chooses the one that optimizes the power in reference to a target power. As a secondary optimization criterion, this *d*-function also maximizes the open-circuit voltage of the array.

Technical information about the available components is arranged as tables and implemented as .txt files. They are directly used by the *d*-functions. For instance, in F4 the file "Pumps.txt" is used to check for the availability of a pump system that can overcome the total dynamic head of the application. Note that, by the addition of new pumps to this table, the total dynamic head limit of the configurator can be increased.

Figure 5 shows the general algorithm for the SPPS configurator. At the centre, it can be seen the *d*-functions (numbered F1–F17), each one representing a subVI (a kind of routine in LabVIEW), with the variables to which they are attached at the right of the diagram. The variables to which the *d*-functions depend on are indicated by the connection lines from below. The arrangement of the *d*-functions in the diagram clearly reveals the dependency between variables. As it can be verified, there is no dependency loop between the variables. At the left of the diagram, it can be seen the control structure which operates in conjunction with the loop structure (the outer structure encompassing the whole program). Initially, only the first four *d*-functions will be executed. If the abort condition in the *d*-function F4 is true, there is no solution for the configuration problem and the program ends. Otherwise, the abort variable is set to false and the other *d*-functions are executed. As the *d*-functions are executed, they generate the values for the correspondent variables and are set to inactive. *D*-functions attached to variables (other than the inclusion variables) on components that will not be included are set to inactive without generating values. When all the functions are inactive (which is equivalent to $F = \varnothing$ in the control algorithm in Fig. 3), a solution has been found and the program ends. This happens in exactly three iterations of the configurator program.

Figure 6 shows the solution of the CN-F model found by the configurator after a test case for the values of the input variables. The values of the output variables

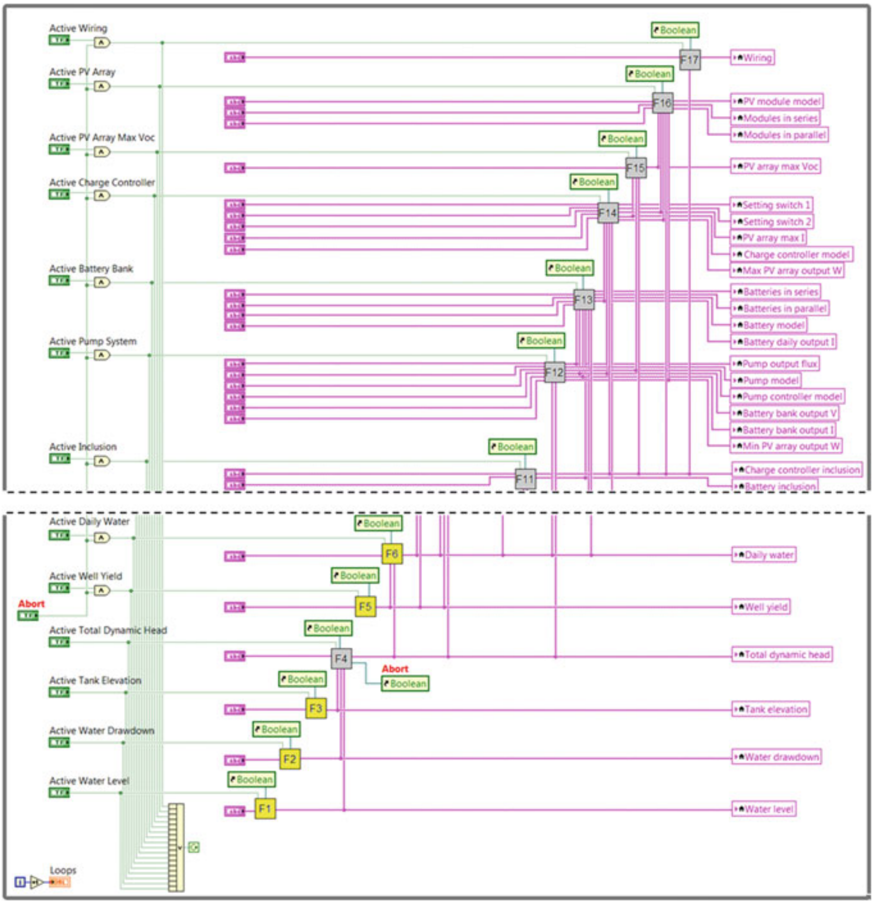

Fig. 5 Excerpt of the general SPPS configurator program implemented in LabVIEW

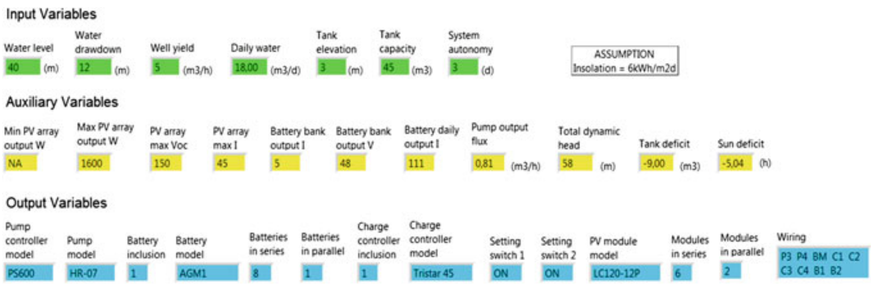

Fig. 6 Simplified interface of the SPPS configurator showing the solution for a test case

specify the member of the SPPS product family that meets those requirements. For an illustrative purpose, the auxiliary variables and their values are also displayed.

The program described above was ported to Windows Mobile 6 professional, ARM920T Device Emulator. Tests with the emulator showed that after all the customer requirements have been input, the time to obtain solutions was in the order of milliseconds.

6 Conclusions

In this paper, we have shown that the configuration process of the SPPS product family can be arranged into a direct method by the concatenation of the *d*-functions into a dataflow process. Because LabVIEW is a programing language based on the principle of dataflow, it proved to be an interesting choice to put that property in evidence.

The short response times of the SPPS configurator running as standalone program on an emulator for mobile devices demonstrate its viability as a tool for popular devices such as smartphones and tablets, without Internet connection. This also implies that there is room for the design of a much more sophisticated configurator without compromising its responsiveness on the mobile device.

Besides the performance, another conspicuous advantage of our approach is the level of modularity that can be obtained. The resulting software program is such that any *d*-function can be improved without affecting the other functions or the control structure. The same is true for the introduction of new *d*-functions. For example, we could have included a *d*-function that automatically defines the insolation level from the location of the well. Moreover, because the available components are given as .txt files, new components can be included independently from the *d*-functions. All these features will facilitate greatly the maintainability of our configurator.

Finally, it is important to note that, besides the correct configuration of the SPPS, configurators may have a major role in the automation of the total sales cycle, thus giving a further competitive advantage to the company [11]. This was outside the scope of this work. However, tasks such as the preparation of the quotations and bill of materials could have been included as additional *d*-functions.

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Implementation of BIM in the Danish Building Sector

Lene Faber Ussing and Jesper Kranker Larsen

Abstract The Danish building sector has now for some years worked for implementation of BIM in the whole building process. In practice, it seems with the long way from the wish of using BIM in the whole building process to what really happens on the projects and building sites. To get an idea of how long the BIM implementation has come in the sector, a contractor company at present involved in one of the biggest public construction projects in Denmark was contacted to survey some employees at the project, because such a project ought to be one where BIM is best implemented. This survey shows the building sector is implementing BIM, but there are still big challenges to solve both internally in the company and externally both in the immediate environment and distant environment.

Keywords BIM · Building sector · Communication · ICT · Public construction projects

1 Introduction

The building sector is frequently described as conservative and tradition bound, which according to critics results in little innovation, a not very efficient and effective cooperation and bad economy compared with other industries. The wish in a lot of building projects is customization. A method to be more efficient and

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effective is to use mass customization in house building in a way where the building owner seems it as customization [14]. The Danish building sector has for one thing used BIM to make mass customization.

The sector has now for some years worked with the implementation of BIM in the whole building process. The engineers and architects work for going from 2D drafts to 3D modeling in expectation of being more efficient and making less faults and imperfections in the completed building [2]. In 2007, the Danish government worked out an executive order treats information and communication technology (ICT) in public construction projects which meant that all involved parties in a public construction project suddenly needed a sort of 3D modeling to fulfill the executive order about ICT in public construction projects.

When BIM is discussed with engineers, architects, contractors, and suppliers, there is still a long way from what the Danish government wants in the future with ICT and BIM and what really happens on the Danish building projects and sites.

The engineers and architects are going from 2D to 3D drawing [4], but a lot of them do not use the part of the programs where you can put in the time and the costs. The explanation is that they are not being responsible for time and costs; the contractors and suppliers have to calculate these themselves. The contractors and suppliers do not have the software to use 3D [15] and BIM because it is too expensive. So it is the Gordian knot if the engineers and architects will not use the whole software and the contractors and the suppliers will not buy it because they see no advantage [3].

Therefore, the project aim is to have a look at one of the big public construction projects which actually demands use of ICT in the whole process of the project.

2 Research Methodology

The purpose of this paper is to seek partly answers to the research question: How does a contractor in Denmark implement BIM in his organization and does all in the company he knows about and uses BIM? To answer the question, the biggest contractors in Denmark have been examined. They all make public buildings, and therefore, they have to follow the rules in the executive order about ICT in public construction projects. They have all made some initiative and development projects to diffuse BIM in the respective companies. Three master students at Aalborg University recorded in their company internship program at three of the biggest contractors in Denmark that the companies may have implemented BIM, but the employees did only in a limited degree know about the initiatives and development projects diffusing BIM. Therefore, the three students decided to write their Master thesis about a survey of some employees at the contractor company at present involved in one of the biggest public construction projects in Denmark, because such a project ought to be one where BIM is best implemented.

2.1 The Survey

The survey was made as qualitative interviews. All interviews were made as semi-constructed interviews where all questions were designed with open main questions and if necessary supported with open subquestions to secure an open and pleasant talk for the interviewees [5, 13, 17]. To ensure all communication such as voice and body language, etc. of the interviewee, the interviews were made face to face where the advantages are a communication where interviewee will answer spontaneously and with a reduced chance of reflection at the questions [12]. On the other side, that gives the interviewer a challenge and opportunity to create a good atmosphere during the interview session [16]. To avoid interviewee feeling "observed" and "used" by researcher, [9] interviewer and interviewees were communicating a few times to create trust and confidence [11].

The interviewed persons were a BIM manager from the strategic level in the organization who was not directly involved in the big public construction project, a BIM coordinator from the tactical level in the organization who was the connection between the general organization and the single project, a project manager, and a concrete foreman both from the operational level in the organization and both placed on the same big public construction project.

The interview study is compounded by questions about formalities like what is your job? How do you define BIM? And how and when do you use BIM? and about the planning of implementation of BIM like how have the employees been trained and prepared for the implementation? What do you feel about the process of change and how do you deal with it? Where and who pays for the implementation of BIM? and the practical implementation like how has the BIM strategy been accepted in the organization and on the pilot projects? What has been the biggest challenge? And what has been the greatest success?

3 Findings and Discussion

3.1 Formalities

The first question was to clarify whether it was the right persons to be interviewed what is your job? As mention before, four people were interviewed (Fig. 1);

- The BIM manager who is responsible for development, implementation, and performance of BIM in the company.
- One of the BIM coordinators, who is employed in the quality division, but the salary is paid by the BIM division so the coordinator refers to two divisions. The coordinator is affiliated to the big public construction project and some other projects which needed help for support of BIM and the coordinator also teach in the use of BIM.

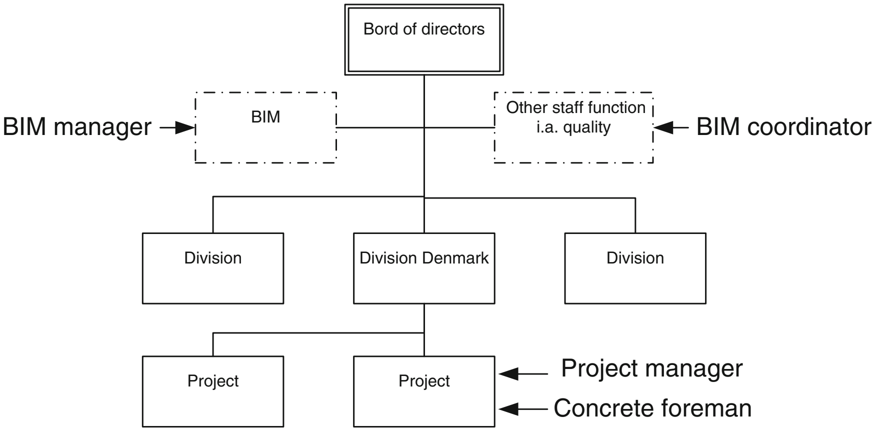

Fig. 1 Organization chart showing where the four interviewed are placed

- The project manager of the big public construction project, who has the daily leadership of the project such as procurement and contracting of subcontractors, management of time schedule, management of own production, and dialog with the building owner.
- The concrete foreman of the big public construction project, who is responsible for 40 men—15 engaged with prefabricated concrete construction and the rest engaged with in situ concrete. The primary work is scrutiny and project clarification.

Those four people were picked out so that they together represent each level of the company, and therefore, they can describe the opportunity of their level in the company to implement BIM in the organization.

The next question was how do you define BIM? The question reveals whether an agreement is reached in all level in the organization of what BIM is. The upper level (manager and coordinator) defines BIM as many things going from 2D over 3D sketches linked together with time and economy to a process where in the future you end with a sort of digitized building work, whereas the lower levels define BIM only as 3D modeling. The company has not defined an unambiguous definition of BIM because they do not want the employee to be limited by a definition. This can have two solutions. One is that the lower level does not see the whole plan and another where some good ideas pop up which the board of directors did not see. The last one is wishes which have not happened yet.

Another question is how and when do you use BIM? The upper level tries to help the rest of the organization to use BIM to as great an extent as possible. The boards of directors want to implement BIM as soon as possible, but it has to be a voluntary choice, so the results are that the lower level use BIM mainly for visualization, navigation, and scrutiny. The project manager also sometimes uses BIM to verify an amount from a tender.

3.2 Planning of Implementation

The first question was how have the employees been trained and prepared for the implementation of BIM? To answer to the question is in agreement at all level. The overall BIM strategy was presented on a BIM conference in autumn 2012. After the conference, the employees were informed on divisions meetings and there was ongoing information by mails with newsletters. The newsletters were to the interviewed project manager and the concrete foreman without value. So there has been a quite good planning of the implementation. But the lower level still felt that they did not know why the board of directors wants to implement BIM in the company, the purpose of BIM for the company, and what the strategy about BIM actually was. But as mentioned before, the board of directors has been conscious of their decision. Hopefully, it gives more useful inputs than frustrations in the long run.

Another question was what do you feel about the process of change and how do you deal with it? The upper level finds that the process has been good. The BIM manager and the BIM coordinator have both been deeply involved in the process because they had to implement BIM in practice in the company. The lower levels represented by the project manager and the concrete foreman find that some of the process had been good—the conference and the course programme, but when it was decided to go for conferences and courses, there had been a dilemma with the top level saying the employees had to go to the courses and all the project manager saying the employees had not to go until the work on the site is finished.

The last question was where and who pays for the implementation of BIM? The project does not pay for BIM. It is the BIM division which pays for hardware and software, and the employees division pays for own employees' training and courses. Not all have yet been trained and have not attended courses. In 2012, 600 employees started a course programme. It is the project which decided how many and who has to join the course programme, but it is the BIM division which decided which projects are relevant for using BIM. In that way, it is usually motivated and interested employees who join the course programme without direct cost for the project.

3.3 Practical Implementation

When it comes to the implementation in practice a question was how has the BIM strategy been accepted in the organization and on the pilot projects? The employees have gone from opposition to BIM because they did not know what BIM was to no opposition to BIM because some of the employees now know what BIM was; they have got some BIM competences, and they see BIM as an instrument for doing their job better, easier, and cheaper. The lower levels see the same, but when there is a time conflict between doing something on the project and being better at BIM, the project will still win because you still have a contract which requires delivery at time, have the right price, and the building owner has to be satisfied [1]. In practice, this causes the implementation to take longer time, but hopefully it is worthwhile the effort [8]. Generally, the head organization is positive prepared for BIM, but on the projects, there is still a long way; most of the employees are positive as long as it does not conflict with the project.

Another question was what has been the biggest challenge? That question can be split up into two parts: internal challenges and external challenges.

Internal challenges For the BIM manager, there has been no big challenge internally in the company.

The BIM coordinator still has and had a lot of challenges; lack of experience, in practice the hardware and software are not good enough at the site, the BIM focus can be too high instead of just using BIM as an integrated part of the project, the coordinator has to argue for the use of BIM, and the individual employee's competences about BIM are only known by his or her chef and are not written down. This means that the knowledge will disappear with a chef who leaves the company, and furthermore, it is not easy to plan further education in BIM if you do not know who has which qualifications.

The project manager and the concrete foreman have nearly the same internal challenges; some of the chefs are barriers because they are negative toward BIM, and the chef can decide that an employee does not have to follow a BIM course. At the same time, there is a depression in the Danish building sector, which means that some of the employees are under pressure and therefore act according to the best here and now solution instead of using BIM and to get a long-lasting good solution. A challenge also exists between the different divisions, between different tradesperson, and young and old employees. The gap is going from very positive and persons who want to learn new things because it is exciting, to persons who are negative, afraid of new things and only wants to do as usual because they then think they are safe. The last challenge is that some building owners insist on using special software for BIM. A good deal of software for BIM exists and if the software is different from project to project have to start from scratch every time.

It seems that the upper level, represented by the BIM manager, does not see any internal problems. But the longer we move down in the levels, the bigger are the problems or challenges. A general issue for the company can therefore be to solve the problems the manager and the board of directors do not see.

External challenges For the BIM manager, the biggest challenges were external. The most important of them all is to work with BIM in a country like Denmark and in the building sector. In Denmark, all the norms are made nationally though many good examples on classification and ICT treatment can be found from other countries [5]. The Netherlands has chosen to use American standards. The standards have been reworded and rephrase both in Dutch and English. Some in Denmark are working on making Danish standards, and the Danish educational system is educating candidates who only learn Danish norms which means the companies have to go abroad if they want to obtain international experience and competencies.

For the BIM coordinator, the external challenges have been legal barrier and problems with collaboration abroad due to lack of expected competencies [4] and therefore resulting in incomplete project material, discussions, and delays [6]. The external advisers have been difficult to contact, they do not want to exchange expectations, and they and the subcontractors do not always work at the same BIM level as agreed.

The project manager and the concrete foreman have had some of the same external challenges as the BIM coordinator. The external advisers have not incorporated the contractors and the workmanship in their project and models. The advisers only incorporate things which are of value for themselves. The use of different software does not always work, and sometimes drawings did not match because they come from different software. Another problem is that the advisers who make the drawings do not supervise on the site too, and the contractor is not allowed to contact the advisor who made the drawings directly. This again results in a lot of discussions and delays. The legal contract on the project is based on 2D drawings, but the building owner demands BIM material in the final product. The last challenge is the suppliers. Most of them are quite conservative, and they still only use 2D drawings.

Again, it seems that the upper level represented by the BIM manager does not see the same external problems as others. It is a general issue for the company to solve when the manager and the board of directors do not discover it.

The biggest success The last question was what has been the biggest success? For the BIM manager, the biggest success was going to a branch meeting where all department heads discussed BIM in the production. This indicates that some activities have an effect and succeed after all.

For the BIM coordinator, the biggest success was that the 3D models were so visual that communication was much easier, and for the first time, it was easy to read the exact amount directly from the drawings.

For the project manager and the concrete foreman, the biggest success was the visualization. The planning and contracting had been easier because of localization and the opportunity to see exact amounts in the systems. Potential problems were detected earlier with the advantage of a better quality of the project. It is a big advantage to have a BIM expert on the site, which gives the opportunity to ask when problems arise instead of waiting for half a day.

4 Conclusion and Further Research

This case maybe describes one of the projects in Denmark with major use of BIM. But the interviews show that there still is a long way to go before a project can be found where BIM is used in an optimal way. The question is whether the company implements BIM in the right way. Planning of the implementation seems to be all right but with some minor errors which have to be adjusted in the future.

The practical implementation on the other hand was with major errors. The BIM manager did not see any internal challenges despite the fact that the BIM coordinator, the project manager, and the concrete foreman saw a lot of challenges. Some of the internal challenges can be solved easily; for instance, employees who are negative and do not have the right BIM knowledge. The company can send these employees on courses together with the positive and interested ones, but first, the BIM manager and the board of directors must see the problem and make some registration on the employees' BIM education, knowledge on BIM, and interest in BIM. They must make a decision on whether to use BIM or not. If the answer is to use BIM, then there has to be an official written BIM strategy, some written rules about use of hardware and software so an employee cannot use what he/she finds optimal, and all employees without exception have to be educated in BIM. If the upper level does not take such a decision, the risk is that BIM will not be used any further. The company now uses BIM "for fun," use it when you want. The result could be that BIM will not be used in future or it will take a very long time before all use it. If the company really wants to use BIM, some financial support for education of all employees is required together with some time for key BIM persons; part of the work has already been made so it is a shame not to complete the last part internally in the company.

Externally, the company experiences nearly the same problem. The BIM manager meets problems going aboard with different standards which the manager cannot do anything about in a short term, but people who have direct contact to the projects see and live with small external problems in the immediate environment. Some of these problems can maybe be solved by solving some of the internal problems. If the company has an official written BIM strategy and some written rules about use of hardware and software, then the company's collaborators as advisors, subcontractors, and suppliers will know that they have to follow these rules. It can also be easier for a project manager to choose his/her collaborator if requirements are written down. Then, they can say whether the collaborator is qualified or not and a lot of discussions will end and maybe we will get a better quality of projects in the future.

To get a better implementation of BIM at the building project in general, BIM must be required by the building owner and in the project organization, but it also requires education and development of workable software. Financial support is needed, and the Danish building sector is not known to have much money. A solution can be more pilot projects where the government gives some money for special parts of BIM and in that way takes one workable step at a time. If the projects in the same way have to fulfill the wish of customization, a method to be more efficient and effective is to use mass customization by taking appropriate lessons from the manufacturing sector which involves a mixture of standardized components [14]. Standardized components can also make the use of BIM easier.

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InnoTracing: A Framework to Investigate the Moment-to-Moment Unfolding of Leadership, Creativity, and Innovation

Ian Sutherland, Paul Blazek, Birgit Penzenstadler, Hans Lundberg and Hagen Habicht

Abstract In researching the crucial drivers in innovation processes, it becomes more and more clear that social interactions at a microlevel play an important role when it comes to user innovation. InnoTracing sheds light on understanding what happens in the black box of emergent, situated processes by looking at what participating users regard as their particular "moments of significance" (MOS). The usage of the newly developed software tool InnoTrace allows real-time data gathering, aggregating, and analyzing and works within the methodological concept InnoTracing as fundamental enabler for identifying previously invisible innovation and leadership effects. This software and methodology combination offers researchers and companies the ability to understand how collaboration processes among innovators work and provides valuable insights on how to create a supporting environment.

Keywords Innovation · Leadership · Traceability · Management · Software

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1 Introduction

Group processes are complex, nonlinear, recursive, unpredictable, and largely tacit [45, 54]; this is particularly true for the elusive and ephemeral phenomena of innovation and leadership [2, 12, 24, 33, 47]. Despite decades of study, theorization, and modeling, the moment-to-moment unfolding, the microlevel of interaction, of these processes remains an unexplored black box. The InnoTrace software and methodology have been specifically developed to address this lacuna. The central methodological problem has been the imposition of researchers, and their biases, on such systems in identifying significant moments, events, and actors [29, 54]. Whether using survey methods, interviews, focus groups, participant observation, or any of our other familiar data-gathering processes, researcher bias influences the data gathered. What has been lacking, in terms of interrogating social interactions at a microlevel, is the empowerment of research participants in generating the data themselves. InnoTrace is a bespoke tool for researchers to put data gathering directly into the hands of participants, to empower them to capture the "moments of significance" (MOS) they experience in unfolding processes, and to aggregate that data for each participant and the whole group of participants—creating individual and group cognitive maps which serve as a rich visual tapestry of the microlevel interactions of group processes which underlie the phenomena of leadership and innovation.

2 Background: Methodological Innovation

In recent years, researchers working on leadership and innovation have been moving beyond their traditional phenomenological and methodological boundaries. There is increasing attention placed on the microlevel, to the situated interactions of participating agents and how—in real time from moment-to-moment—leadership and innovation emerge [29, 54].

Within leadership studies, there has been a turn away from the traditional positivist stance that typified twentieth-century approaches. As an academic discipline that has relied heavily upon psychological and social–psychological methods, leadership scholars worldwide have been making calls for a change, to broaden the focus from studying singular leaders and followers toward contextual relations of interacting, subjective social agents [29, 30].

At the heart of this, shift has been a questioning of the basic ontological and epistemological assumptions of leadership and its study. As scholars such as [2, 3, 30, 31, 52] have questioned the very nature and study of leadership (even if "it" exists), there has been a movement toward social–constructivist views of leadership; that as a phenomenon, leadership is constructed, maintained, changed, or dispersed at the microlevel of interactions between a variety of social agents acting within contextualized times and spaces [1, 16, 23, 33, 37, 41, 47]. As a result, a number of closely related theories have arisen from this more sociological, emergent, and "in-action" view of leadership. These include distributed leadership [9, 24, 44], collective leadership [18, 36], shared leadership [41, 42], and relational leadership [47]. Such theories treat leadership as a more complex, dynamic, and "messy" process than the leader-centric or follower-centric theories that have proliferated the literature over the last century.

In a similar vein, innovation research is moving from studying coordination issues of research and development activities within particular departments toward an increased interest in collaborative research efforts which cross organizational boundaries [4]. This change has taken on speed due to the development of social software-enabled innovation methods such as communities and contests [53, 39]. Scholars nowadays recognize various forms of collaborative (open) innovation, be it in the form of interorganizational innovation networks, or be it based on crowd-sourcing mechanisms.

Although this research has produced a variety of studies on individual characteristics [34, 49] and motivators [27, 28, 38, 50] of participants, on success-relevant management capabilities, and organizational characteristics [13, 21, 35, 54] as well as on expected outcomes [20, 48, 49], the microfoundations of collaboration among innovators have to date remained a black box. In particular, studying the in situ unfolding of creativity on the group level, such as by tracing the actual process of identifying and spanning of boundaries, or the self-reporting about direct group-level effects of self-rewarding activities (e.g., group flow), would lead to new insights on the actual foundations of collaborative innovation. Yet, ultimately, these concepts and theories encounter a methodological brick wall as researchers face the difficulty of getting to the in situ, socially constructed dynamics of leadership and innovation unfolding in real time. What is missing is the ability to visualize the seemingly invisible, moment-to-moment emergence of such collaborative processes at the situated level of individual and group action as people interact in space and time.

In leadership research in particular, there have been a number of new methodological calls resulting from the desire to explore the level of situated and subjective social action. Crevani, Lindgren, and Packendorff [16] have posited "…an analytical focus on leadership as it is practiced in daily interaction" (p. 77). Iszatt-White has engaged an ethnomethodological approach of 'mutual elaboration'—"…the idea that an action only makes sense, has meaning, in the specific setting in which it is enacted—to explore leadership practices as irreducibly 'events in a social order'" [29, p. 120] . This approach "pays attention to, and seeks to make visible, the 'ethno-methods' [22] through which the social order of [a] setting is inter-subjectively constructed…" [29, p. 124].

Parry [40] and Kempster and Parry [30] have been advocating for a grounded theory [14, 15] approach to studying leadership as methodological means to moving beyond the ontological and epistemological assumptions that chained leadership to its singular or dyadic focus upon leaders and followers. They have noted "Leadership research has begun to embrace the necessity of incorporating context and process into an understanding of the manifestation of the leadership phenomenon" (p. 106). With its focus on generating contextually relevant theoretical explanations for experienced phenomena based on the subjective actions and perceptions of agents within a given context, grounded theory matches the contemporary directions of leadership and innovation inquiry. Still, others have proceeded with inquiry into the esthetics of leadership, focusing on the felt, sensory–emotional aspects of leadership in action [7, 25, 26, 32].

At the basis of these sociological approaches toward leadership and innovation—that they are phenomena emerging from social interactions, irreducible to the actions of single individuals—is a call to look at the moment-to-moment experiences and perceptions of emerging processes. Working from a process philosophy standpoint, Wood and Ladkin [54] argue that "Rather than focusing primarily on the individual leader, or even the dyadic relationship between leaders and followers, the lens of process philosophy frames leadership as an unfolding, emerging process; a continuous coming into being." [54, p. 15]. Yet, here, we find a methodological quagmire. The ability to investigate the continuously "coming into being" of human interactional phenomena is trying to make the invisible of highly complex interactions visible. There are no methodological tools ready-made for this task. While we may seek to investigate it through ethnography and conceptualize it as an ethnomethodological process (such as argued by Iszatt-White [29]), we run up against problems of observer influence and interpretation. Similarly, we often find ourselves in the realm of ex post facto research and analysis when what we really desire is to, as Wood and Ladkin [54] have suggested, focus on the level of participating actors' perceptions of the moments of the phenomena.

What is required is a methodological approach that empowers participating agents to document and comment upon significant moments as they relate to leadership and innovation—what InnoTracing refers to as (MOS)—as they unfold in real time. This is the core of the InnoTracing project, to provide participants and researchers insights into these seemingly invisible moments when "something" seems to be happening. The InnoTrace tool allows participants to capture—via picture, video, text, or voice notes—moments which feel significant in the unfolding, emergent processes of leadership, and innovation, as they happen. The resulting methodology seeks to provide a methodological tool to aid researchers in working with the gathered data.

3 InnoTracing: A New Methodology in Leadership and Innovation Research

InnoTracing[1] is a methodological development that combines a unique data-gathering and aggregating software tool—InnoTrace—with social science methods to help researchers and participants open, visualize, and investigate the (MOS) of

[1] http://www.innotracing.org

leadership and innovation. The InnoTrace tool is designed as user-friendly and user-configurable software, affording participants the ability to capture and trace the moment-to-moment messy, tacit, and intangible elements of leadership and innovation. The tool empowers participants to document these moments as they feel them occur in real time (through photos, videos, text files, or sound messages), while the Web-based software collects and organizes this data in a variety of ways. At a basic level, with each use of the InnoTrace software, participants document unfolding processes by photographing, video recording, or creating text or voice notes of the MOS of an unfolding process. The underpinning concept is to empower participants to make "visible" what they perceive as significant (whether the significance is of something positive, negative, or even mundane) in the unfolding processes of which they are a part.

This type of participant-centered data-gathering methodology has anthropological roots where participants have been engaged to visually document their perceptions of the world around them (e.g., [8, 42, 43]). In organizational studies, precedence has been set in studies by Buchanan [11] and Warren [51] where they have investigated the esthetic experiences of individual social agents, asking them to photograph elements of their daily experience to make visible "how it feels to work here" [51]. Within leadership research, Wood and Ladkin [54] involved participant managers and organizational consultants in photographing "…those usually hidden elements, which they perceived as contributing to the experience of leadership in their workplaces" (p. 15). In studies on the microphases and participant roles in innovation groups, both in physical and virtual settings, researchers have used a variety of tracing approaches including audio and video recording, screen shots, and versioning/history functions of activities on collaboration-supporting innovation software [5, 6]. Despite the valuable insights that have resulted from these research initiatives, a systematic means of gathering, aggregating, and analyzing participant-generated data is still lacking.

As a researcher-configurable tool, InnoTrace provides a unique platform for participant-generated data. The standard five-step process is as follows:

1. *Phenomena of interest* With each project, the researcher(s) indicates to the participants the phenomena of interest around which they would like to gather MOS. For Wood and Ladkin [54], this was "hidden elements" which contributed to the experience of leadership. For Warren [51], it was the visualization of "how it feels to work here." With regard to leadership and innovation processes, it may be tipping points when things coalesce or take new directions.
2. *MOS Tagging* Within the tool, researchers can include a variety of classification options (tags) or leave tagging open to the discretion of research participants. With each data entry participants can provide their own tag, or in the case of researcher specified tags select from available tags. Additionally, in the case of open tagging, participants may select a tag from the cloud of tags generated by all research participants. These may be descriptors such as "leadership moment" or "idea generation" or "insight" and/or they may be evaluative

elements that classify the importance of a moment (e.g., a star rating indicating relative level of importance or impact of a moment).

3. *Participant-Generated MOS* The tool is made available to research participants who, following the *Phenomena of Interest* outline and using *MOS Tagging*, engage in gathering data on the MOS of processes in which they are involved.
4. *MOS Aggregation and Visualization* As research participants gather data, the InnoTrace software collects and organizes this data by user, time, format, and tag:

    (a) *User*: Each data element is registered as generated by a unique author. This provides indication of who generated the data as well as frequency and quantity analyses of the overall data set by individual author. Through this, the data set can be viewed as a whole, or segmented to look at individual participants or groups of participants.

    (b) *Time*: Each data element is registered by when it was created. This provides indication of the frequency and quantity of data as it was generated chronologically. Through this, the data set can be viewed as a whole (providing a distribution view of MOS over time) or segmented to look at specific time periods.

    (c) *Format*: Each data element is registered by the type of format used (photograph, video, text). Through this, the data can be viewed as a whole indicating the overall types of formats used, or segmented to look at one format type at a time (e.g., to look at all photographic data generated).

    (d) *Tagging*: Tagging is the process of using a descriptor or evaluator tag for data points. This may be left to the discretion of users or specified by researchers. Through this tagging, the data set can be segmented by participant-generated classifications.

In total, the gathered data represent a cognitive map of the happenings in the group. More precisely, it is a shared or composite cognitive map [17, 45] of group processes. It aggregates the perspectives of the group members in the form of a joint context map (as opposed to a strip map) [19, 46] comprising decisive events along with their respective contexts. It thereby enables a better understanding of the boundary conditions of activities [46].

The meanings assigned to the uploaded representations of MOS represent "labels" [10] whose creation—in contrast to traditional cognitive maps—is not exposed to any researcher's interpretation. As a result, anything gathered by the InnoTrace software can be seen as unbiased (uninfluenced) situated data collected by self-reflective participants in the moment.

For this pilot study, participants were given an overview of the InnoTrace project and software, along with a short (5–10 min) training session upon their arrival at the conference. In the main exhibition space of the conference, volunteers (who came to be known as "InnoTracers") were greeted by members of the InnoTrace team as they arrived at the InnoTrace exhibition table, given their unique cowtags—which included their unique username and password printed on the cowtag, and then the project overview and training session. Each username was anonymized (e.g., test1@innotrace.com) to maintain participant confidentiality in generated data.

Within the explanation and overview of the project, participants were instructed on how to use the software (practice runs at logging in and creating test data points), the phenomenon of interest, and MOS tagging. Regarding the phenomenon of interest, participants were asked to "document MOS of your learning experiences during the conference." This explanation was deemed wide enough to allow participants to be free as to what they interpreted as significant. Regarding MOS tagging, the research team decided to allow participants full discretion to create their own tags for data points. During the conference, as the tagging increased, multiple users began using existing tags from the growing tag cloud visible in the InnoTrace application.

4 InnoTrace Software Development and Programming

The development of the easy-to-use software tool InnoTrace[2] proved to be a crucial task in this project. The programmed data storage is utilizing a modern NoSQL solution: MongoDB[3] was chosen because if its broad usage, stability, and the ability to freely modify and update the data schema during our iterative development cycles. The back end, powered by Java, is leveraged with the power of the Restlet Framwork[4] to provide the possibility of a REST API. Communication between the server and the client is completely done with the help of JSON.[5] Using such a RESTful approach has the advantage of being completely transparent to the client system as well as easily replaceable since the technology that REST is based on is regular HTTP. A custom authentication and authorization system with a sophisticated access control system guaranteed a fine-grained control of user access. Such a system paved the ground for many different user privileges to ensure flexibility in terms of what a user is allowed to do. Google's "Dart Language"[6] as the client development platform—although in its early development stage—proved to be a good replacement for traditional JavaScript applications. With the decision to create InnoTrace as Web App, a high flexibility in terms of usage on different devices could be achieved. The user interface design reacts in a responsive way on the display possibilities of the user's devices and minimizes user irritation with its clear and simple interaction process (see Fig. 1).

[2] http://www.innotrace.org

[3] http://www.mongodb.org

[4] http://www.restlet.org

[5] http://www.json.org

[6] http://www.dartlang.org

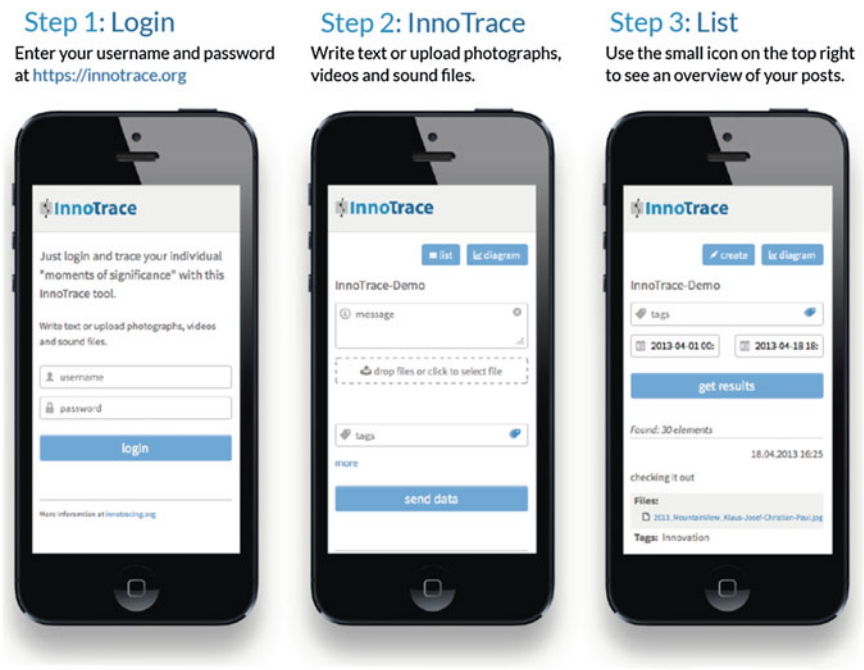

Fig. 1 Screenshot of steps to get started with InnoTrace

5 Analysis and Initial Findings

Data gathered through the InnoTrace application can be used for most forms of qualitative analysis as well as for quasi- and descriptive statistics. The data are open to all the forms of analysis that have been developed for participant-generated data including cognitive maps such as the creation of submaps, e.g., identity maps, cause maps, categorization maps, social system maps, hierarchic maps, and cybernetic maps [25]. Moreover, quasi statistics can help in estimating the centrality of issues or incongruences between different views present.

While the above-described process is the essential methodological approach offered by InnoTracing, it is purposefully open-ended, particularly regarding analysis. InnoTracing is itself a researcher-configurable methodology. Using this basic structure, researchers may approach the data-gathering and analyzing methods in ways best suited to their research questions and goals.

We are currently analyzing the accumulated data sets of the first case studies that allow insights on the study subject of MOS in leadership and innovation as well as different usage scenarios for the tool, e.g., usage as protocol, for personal comments, personal reflections, abstraction and transfer insights, and feedback on the tool itself.

6 Conclusion

This paper presented InnoTracing, a framework to investigate the moment-to-moment unfolding of leadership, creativity, and innovation, and gave a preview of the software tool InnoTrace that is the prototypical realization to implement the concepts.

The impact of our work is that it provides researchers as well as practitioners with a means to gather data on and analyze the nonlinear and largely tacit (group) processes that take place during workshops, seminars, or over longer periods of time in any working unit. Practitioners might not have the complete theoretic background for a full-fledged phenomena analysis, but they may well get insights by performing statistical analysis and reflecting on the data sets.

Our next steps are to analyze the data sets of our first case studies, to extend our set of studies to other application scenarios and to different industry sectors, and to develop a stand-alone version of the tool that can be used off-line.

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Introducing Mass Customization to SMEs in Furniture Industry: A Case Study

Nikola Suzić, Zoran Anišić and Cipriano Forza

Abstract Even though much insights has been gained by academic research on mass customization (MC), companies still suffer from a lack of guidelines and supports that help them in the process of implementing MC. The paper presents an approach to help small and medium enterprises (SMEs) in implementing MC by illustrating its actual application in SME operating in the furniture industry. Possibilities of MC implementation in the case company and more generally in the SME furniture manufacturers are discussed in the conclusions of the work.

Keywords Mass customization · Furniture industry · Implementation analysis · Case study

1 Introduction

Mass customization (MC) is a concept that has been around for more than 20 years, and since the first literature appearances [1, 2], it has been discussed, well understood, and recorded in work of many researchers. But what is clear to researchers specialized in MC may be far from the comprehension of a number of time-pressed managers and engineers working in SMEs. This is also due to the fact that MC is composed of so many techniques, practices, and principles that it takes

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time and appropriate training to manage it effectively in actual settings. Companies will often be in front of the serious challenges when coping with the implementation of MC, challenges such as where to start with the MC implementation, how to proceed with MC implementation, where does it end, what are the effects, what MC techniques should we implement, how much will it cost, how much time and human resources should we devote for this kind of project, what is our current position in implementing of MC, and did we already implement some of the tools without knowing it, what are the possible downfalls, is it a continuous and ongoing job or a one shot project, etc.

Hence, while the research has made considerable progresses in understanding what MC is, what goals does it address, and what are its effects, there is limited guidelines for practitioners on the process of its implementation. There is a need to develop approaches, tools, techniques, and guidelines to help SMEs in the implementation of the MC. It can also be argued that the future will lie in holistic approach of MC implementation [3].

The present paper contributes in covering the need of practical guidelines for MC implementation. It does it by proposing an approach for analysis of the current state in areas where it is possible to identify specific MC improvement initiatives. This approach is structured in four areas of analysis namely

1. Product assortment and part commonality,
2. Sales procedure and product configuration,
3. Production sequence and material flows, and
4. Cost.

Approach is presented by describing a case of MC implementation in a furniture-manufacturing company located in Serbia. By interacting with the academia, this company understood that implementing a MC strategy was very appropriate for its market.

That company realized that the trend of its product variants increased in last few years. These variant increases lead to problems in design, production, and sales processes of the company. Same products with slightly different characteristics were designed repetitively from the beginning, production was not able to meet the deadlines of nonstandard products, and salesmen were not restricted in variants offering to the customers. Furthermore, salesmen were often forced to contact production engineers in order to determine whether wanted configuration is possible to produce. These contacts of salesmen and production engineers had often more than one interaction. Also, nonstandard orders many times lead to mistakes in production which required additional time to correct and lead to dissatisfaction of customers. By applying the proposed analysis approach, this company was expecting the following benefits:

- Better understanding of current state of the company making a clear overview of design, production, and sales processes,
- Getting ideas of how to advance current status of the company and eliminate some if not all of the problems the company encounters,

- Understanding MC concept trough presentation of effects MC concept could have if implemented in the company, and
- Making basis for successful MC implementation.

The situation faced by the given company is common to many SMEs in the furniture industry as well as in other industry sectors too. The presented work is therefore intended to be a first step toward the development of a wider research that will provide SMEs with practical tools and guidelines on how to implement MC.

The remaining part of the present paper is structured in five sections. First two sections present the MC in the furniture industry and provide some information on the furniture industry in Southeast Europe. The subsequent section presents the proposed approach by illustrating its application in a SME operating in a furniture industry. Finally, in the last two sections, the results of the application of the proposed approach are discussed and some conclusions are finally drawn.

2 Furniture Industry in the World and Mass Customization

Furniture industry in the world is in a constant growth. Besides the old players from Europe and North America, today Asia is being more present in this field of manufacturing, especially China whose exports are rising year by year (http://world-furniture-confederation.com/statistics.htm).

As the size of the market grows, so does the interest of the researchers for the area of MC furniture production. There are a number of papers discussing implementation of MC in furniture industry [4], customer preferences for furniture customization [5], environmental issues concerning MC furniture manufacturing [6], data management in customized furniture manufacturing [7], and a number of case studies [8].

The research has also shown that the number of customized products as opposed to mass produced goods is increasing in the world market [9] (Fig. 1). In that sense, many researchers see MC as a strategy of the future for the furniture industry [5]. We can almost say that MC is a must for manufacturers in some countries who are not cost-competent with today’s rules in the furniture market.

3 Furniture Industry in the Region of Southeast Europe

For the moment, there are four types of furniture manufacturing equally present in Serbia: upholstered furniture, massive furniture, laminated furniture, and interior furnishing. Because of a good raw material base and the vicinity of the European market, there is a good possibility for development of Serbian furniture industry.

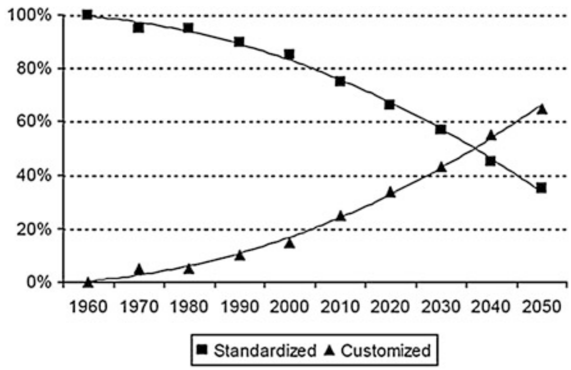

Fig. 1 Market share of standardized versus customized economies [9]

Manufacturing firms in Serbia have, like other companies in the world, undertaken a job of creating an environment for customization. In most of the cases, companies are still implementing customization and not MC. At this moment, we can ascertain that these initiatives are only basic movements in the MC direction.

Small and medium enterprises (SME) sector is maybe the most interested in the application of MC principles, and one of the possible scenarios is that this sector relates closely with the universities and institutes as some researchers openly propose [10], allowing them to pursue a MC concept on the deeper level and with as much as possible low engagement of human resources from the company itself. One such case will be presented in the paper.

Research of the MC concept in Serbia is also making its appearance [11]. Some researchers have already shown [12] that the furniture market of Southeast Europe (particularly Serbia) would welcome MC initiatives and that there is a market for mass-customized products in the furniture industry.

4 Guiding a Furniture Manufacturer Toward MC: A Case Study

The case was analyzed by the support of company personnel, managers, and engineers and was set to be a pre-MC implementation analysis.

Throughout the project, the analysis of the company and possibilities of MC implementation was focused on the following:

1. Product assortment,
2. Sales procedure,
3. Production sequence analysis,
4. Part commonality analysis,
5. Material flows,
6. Basic calculations for product configurator implementation,

7. Impact of product configurator introduction, and
8. Final cost analysis.

Basically, the approach taken in this case analysis follows the procedure for action research cycles proposed by Coghlan and Brannick [13]. Coghlan and Brannick propose four steps: analyze current situation, define and plan the changes that have to be realized, implement the changes planned, and evaluate the obtained results. The presented research was based on first two steps of the mentioned approach. The research was not rigorously structured in terms of analysis sequencing at the beginning of the project, but in some way a bit ad hoc leaving the decision of the next steps opened. The goal was not to be structured, but to have a broad analysis of the company and its capabilities in order to set some grounds for future implementation of MC based on the market needs and company's current product assortment.

4.1 Product Assortment Analysis

In this step, the product assortment of the furniture company was analyzed. Three big groups of products depending on the purpose of use were found:

- office furniture,
- home furniture, and
- furniture for conference halls, theaters, cinemas, etc.

After analysis of the product assortment, the project team agreed that the most interesting part of the product assortment for MC implementation is the home furniture. Specifically, the family selected for the pilot program was the family of sofas, because the most adjustments in the past were done on this product family.

The sofa family is comprised of 8 distinct products with a number of versions that appear in production estimated at a couple of hundred basic versions. This group of products is made from the same materials and intermediate parts. They differ in design, construction, and price.

After choosing the product family, the representative product was selected using the Pareto analysis on sales quotes in the past. One of the "economy" models (named Aphrodite) dominated the analysis (Fig. 2). This was expected knowing roughly the sales numbers in the last few years.

The product was then analyzed by the raw materials used in its production and assembly. In this step, it was recorded that the company has no restrictions regarding the solution space and in order to get the buyer agrees to make changes that characterize the craft production.

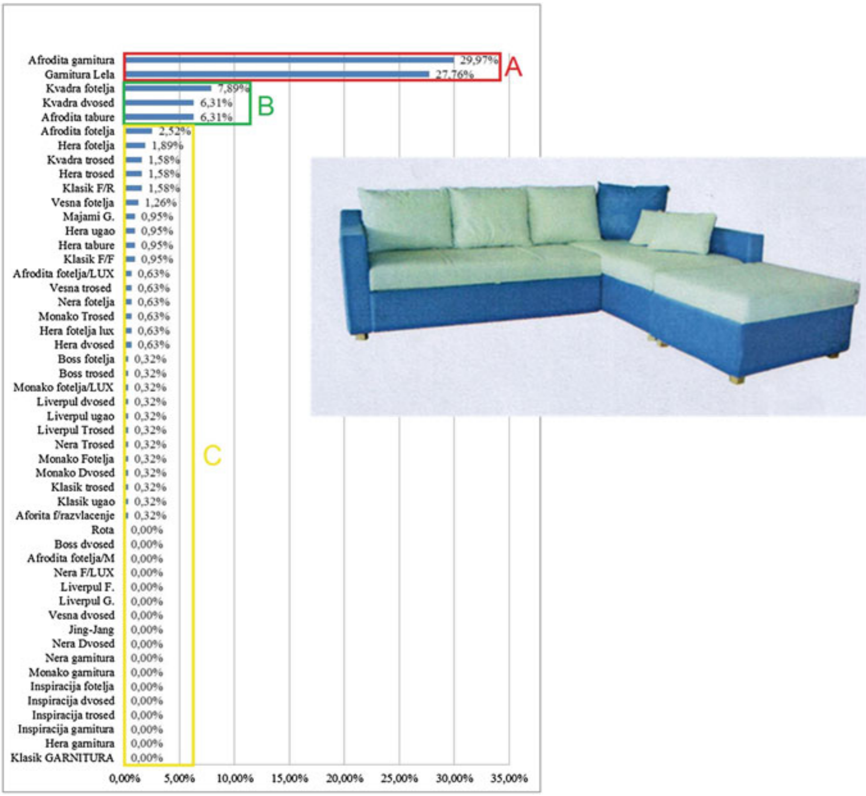

Fig. 2 Pareto analysis and chosen representative product

4.2 Sales Procedure Analysis

The sale of the products is done in a number of ways, but the majority of the sofa families are sold in company's salesrooms directly to the customers. The models are presented in a couple of variants in terms of textile combinations to give a better insight to a buyer on all the options he has to choose from. This is the modality in which the standard sofa models are sold.

As previously mentioned, there is also nonstandard part of the offer. The system functions in a way that the buyer asks for a change in some of the products features. The change request is sent to the producer for approval. Production and design engineers approve or disapprove the change. If the change is possible and can be done, the price for the new product variant is calculated and sent to the buyer. The buyer then decides whether he will buy the product.

The delivery time varies depending on the type of the products. A serial production is delivered in 7–15 days, a standardized product is delivered in 15–30 days, and a nonstandard product may take more time to be delivered.

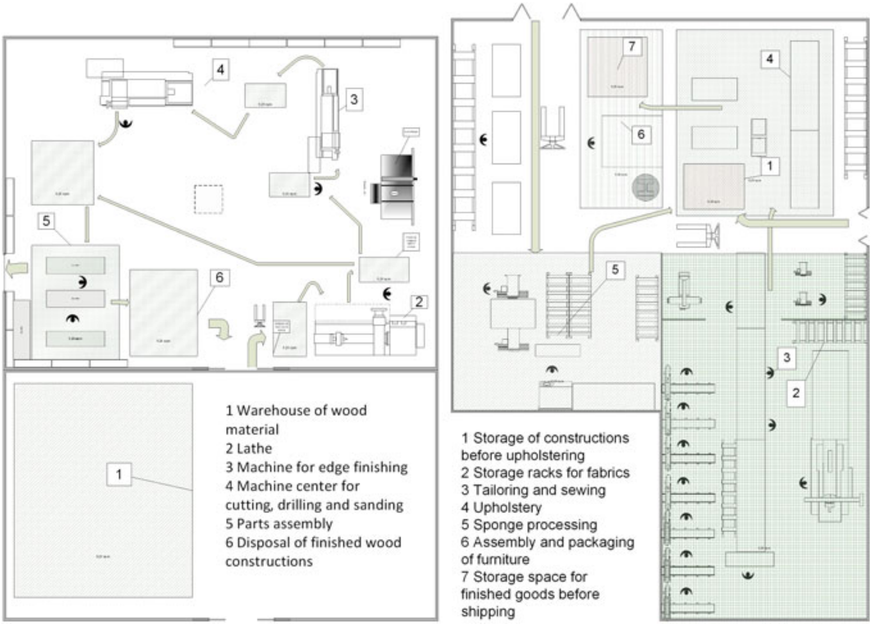

Fig. 3 The layout of the wood processing (on the *left*) and the textile processing (on the *right*)

4.3 Production Sequence Analysis

The production is organized in job shops, grouping the machines of the same type together. There are job shops for the following: sponge processing, wood processing, laminated material processing, textile processing, metal processing, wire core processing, and product assembly. In the production of representative product, sponge processing, wood processing, metal processing, and product assembly are included (Fig. 3).

4.4 Part Commonality Analysis

The complete architecture of product representative was captured in this step, locating common, semi-variant, and variant parts in the product (Fig. 4).

4.5 Material Flows

Material flows of the representative product have been recorded in this step (Fig. 5). Engineers have already tried to reduce the transport of products in the production system to minimum, in order not to damage the products in the movement.

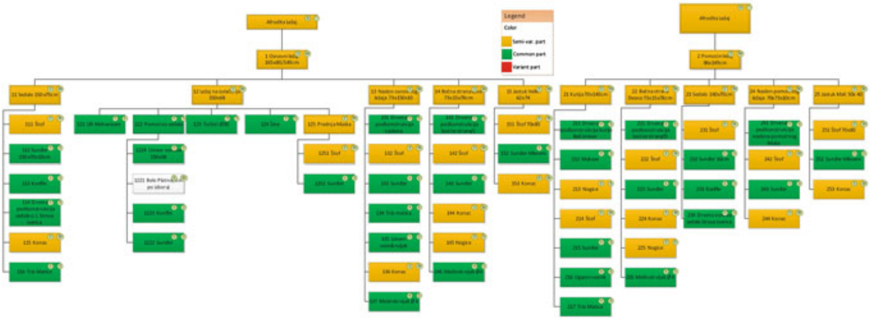

Fig. 4 Analysis of part commonality of product representative

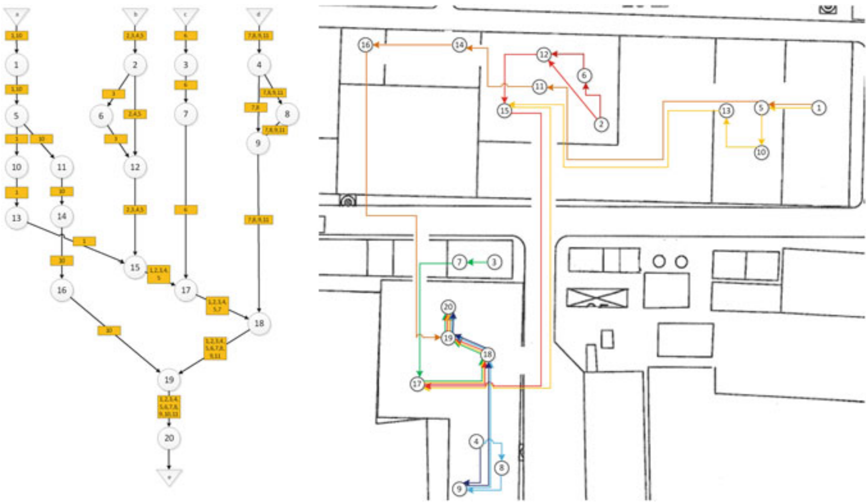

Fig. 5 Recorded material flows in the production system and the real outlook of the flows in the system

4.6 Basic Calculations for Product Configurator Implementation

This step included assessment of cost-effectiveness and evaluation of profitability of product configurator by calculating the increase in production costs and the cost of materials when creating nonstandard products. The increase was compared with predicted increase in sales of standard and nonstandard products. Assessment also included system changes as well as changes resulting from the introduction of product configurator.

Table 1 Defining the nonstandard changes in the product

	Unit A	Unit B	Unit C
Basic part	Sofa side	Basic bed	Additional bed
The change item	Width of the side	Length of the basic bed	Width of the additional bed
Standard size (cm)	15	140	70
Dimension range (cm)	10 or 20 or 25	140 or 180	60 or 70 or 80
Design limitations	Design	Lifting mechanism	Statically endurance
Worst scenario (cm)	25	180	80
Impact of changes on the other product parts	No	Change of the length of basic bed impacts on back-side length (must be equal)	Change of the width of additional bed impacts on back-side length (must be equal)

4.6.1 Creating the Worst-Case Configuration Scenario

In order to have the cost-effectiveness analysis, the "worst possible" product configuring scenario was designed.

To enable the analysis of different scenarios in product configuration, the product was split into the three units: the sofa sides (unit A), the main bed (unit B), and the additional bed (unit C).

Using this division, we defined nonstandard modifications, and of all changes, we chose the ones that make the biggest cost increase in the production (Table 1). The model of nonstandard product was named "ABC model" in the product specification, according to the naming of the units.

Consideration of the worst possible configuration scenario must also take the textile changes into account. The most expensive textile was chosen for the calculations according to the decision that the most expensive version of the product is created.

During the analysis, design limitations were found for every unit of the product (Table 1). These limitations represent main constraints which must be taken into account during the design process for every product configuration. Analysis showed that limitation for sofa sides (Unit A) is predetermined design which is limited by a number of designed variants. For the basic bed (Unit B), limitation is the lifting mechanism which constrains the possibilities to change the size of the bed (length) having in mind mechanical characteristics of the standard lifting mechanism. Additional bed (Unit C) is limited by the statistical endurance, and calculations show that 80 cm is the maximum length that used material can withstand.

Marked limitations are important for purposes of MC implementation in company. They imply that there is limited number of possible variants with current product design, mechanical properties of parts, and materials used. Furthermore, this leads to conclusion that mentioned design limitations are the ones to be worked on in order to create greater number of product variants in the future. The changes could be, for example, new sides design, introduction of new lifting mechanisms, or change in materials for additional bed.

4.6.2 Material Norms

Using the cutting plans defined with the Table 1 and the norms of materials, the total production cost for a standard product "Aphrodite" was calculated. Afterward, the percentage of increase in material cost for nonstandard "ABC" product was calculated. The cost increase went from 0 to 23.55 % by product part compared to the standard product.

4.6.3 Changes in Production

In order to produce a nonstandard product, the changes should be implemented in seven of twenty-one operations in the standard product. In only two of those seven operations, there is a need to change (produce) a new tool. In this case, the cost of the tools is low. Other changes refer mainly to the changes in the CNC codes.

4.6.4 Material Utilization

Because of the lower quantity of the nonstandard products, there is a problem to make efficient "cut-out schemes." This increases the cost of the material. The calculated efficiency decrease is around 5 % as opposed to the standard products. The calculated efficiency decrease varies from the type of material in case, being it the wood parts, the sponge, or the textile. The biggest decrease is expected in textile materials because of the raw material dimensions.

4.7 Impact of Product Configurator Introduction

The differences between the standard product and the nonstandard product in production processes are managed in the work order document. The changes are added in the work order, and the workers follow the instructions. This kind of organization is subjected to the appearance of mistakes. This is the point where the product configurator can give substantial results giving the standard list with the operations to the workers.

The team agreed that the points of configurator impact on the production system would be the following:

- The amount of manual work in taking nonstandard orders and managing the work orders in production would be significantly reduced and in some cases completely left out,
- The mistakes caused by the misinterpretation of the work order would also be significantly reduced,
- Increase in sales is expected after the product configurator is in place,
- The product stocks should be revised with the product configurator and MC concept in place, and
- Stock of raw materials: Expectation is that there may be increase in the raw laminated material stocks up to 20 %, depending on the orders sequencing. The sponge stocks would not change. The textile stocks would represent a problem because of the vast number of textile options. There is assumption that there would be a need to revise the textile list in order to optimize the expenses.

4.8 Final Cost Analysis

In order to calculate the cost-effectiveness of introducing MC into the given company, two types of costs were taken into account: one-time costs and costs per unit of the product.

One-time costs that were taken into account are as follows: product configurator introduction, maintenance of the product configurator, special tools production, worker training, IT hardware acquisition, and minimal stocks build up.

Costs per unit of the product include the following: increased material consumption norms, higher material waste, costs of longer production time, costs of increased assembly time, and increased transport costs.

Total cost of MC introduction per product was then calculated with the assumption of 20 % participation of nonstandard products in the sales in next 4 years. The result was the increase of 23.02 % in cost per unit of the nonstandard product (Fig. 6). The numbers would be more favorable if the nonstandard products would sell more.

The calculations were made in order to predict the additional cost per product sold in the observed period as opposed to the current state in company. All calculations were done in accordance with the prices of the raw materials and labor market in Serbia.

Analyzing the product lifecycle, the project group presumed that the product will be sold in the period of next 4 years with minor changes. The cost analysis was done for that period of time.

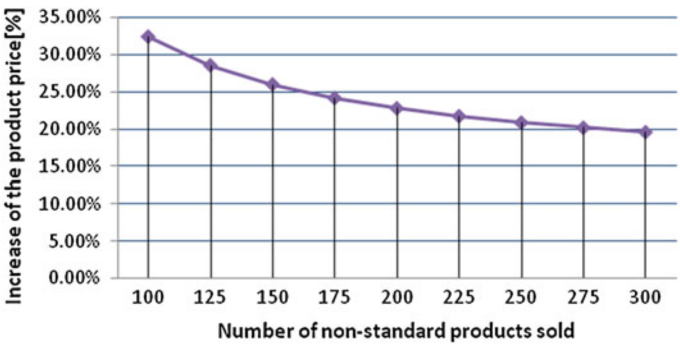

Fig. 6 The percent of price increase per nonstandard products, taking the number of sold products into account

5 Discussion

The research was done with the assistance and full participation of the company management, design, and production engineers. Results of applied analysis steps lead to discussion and conclusions summarized below:

- Proposed method of analysis was graded as applicable and suitable from the company's side.
- Research showed that initial investment in MC would not be of very high level in the company's terms.
- It was concluded that implementation of product configurator draws with it a series of changes in the system itself and in production generally. This fact is known from the corresponding literature [14, 15] and was confirmed in the research.
- Research showed that there are many changes in the company that are needed in order to implement MC and that are in fact very low in costs and only dealing with organization of production, like implementation of form postponement strategy and changing the sequence of the operations.
- The company "convinced itself" that MC is plausible in practice and not so demanding at the start. In-depth analysis of production processes and the product changes done in the near past have persuaded the company management that the changes in products will come being wanted or not.
- The "personalized model" for MC implementation was created for the company through presented project.
- The increase in nonstandard product price has been calculated to be 23.02 % which is close to the theoretical 20 % which the buyer is ready to pay [5]. Additionally, the studied case is the "worst configuration" scenario, where in practice, most of the demanded changes will be minor, leading the price well beneath the 20 % increase.

- Cutting efficiency (laminated material) has also been treated for the worst possible case, where in practice, the more pieces of products are being produced, the waste will be lesser. So we could expect these prices to be lower too.
- The costs were calculated in the 4-year period time, giving the total expenses. The configurator maintenance is the expense that will come in per-month cycles and is to be treated in such a way.
- The costs were treated for the representative model (Aphrodite). It is to be expected that the costs will drop down significantly if the MC implementation would cover the whole product range.
- It can be expected that implementation of the product configurator will rise the sales of other similar products in offer.
- The positive effects of the MC implementation on company were ascertained by both university and company project members.
- It can be expected that with implementation of the MC concept, company would acquire a concurrent advantage on the market and further strengthen its position.

Analyzing results of the research, the project team concluded that a path for successful MC implementation could be derived from the given results and that the steps toward application are to be taken. In this way, the pre-MC implementation analysis based on the proposed method was completed successfully and with valid results showing that MC implementation is possible in the given company and would have multiple positive effects if implemented.

6 Conclusions of the Research

The approach applied in this case company analyses consider the general procedure proposed by Coghlan and Brannick [13] for action research cycles and is adapted to the case of MC. The application was mainly based on first two steps of the given approach: analysis of current situation and defining and planning the changes that have to be realized.

Analysis of current situation step was divided into eight phases in the research:

1. Product assortment,
2. Sales procedure,
3. Production sequence analysis,
4. Part commonality analysis,
5. Material flow,
6. Basic calculations for product configurator implementation,
7. Impact of product configurator introduction, and
8. Final cost analysis.

Based on the research results, we can ascertain that proposed procedure can be applied successfully in furniture-manufacturing SMEs as pre-MC implementation analysis. Procedure reveals problems in company processes and emphasizes critical points for MC application. In result, procedure can lead to proposal of feasible solutions for MC implementation in analyzed furniture-manufacturing company.

Furthermore, it is expected that same procedure can be generalized and applied as introduction analysis for MC projects in SMEs of other industry sectors having the same or similar starting positions like the case study company.

Future research should be focused on the application of proposed procedure in furniture sector as well as investigating possibilities to apply this procedure in other industries.

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Is Sustainable Mass Customization an Oxymoron? An Empirical Study to Analyze the Environmental Impacts of a MC Business Model

Golboo Pourabdollahian, Marco Taisch and Frank T. Piller

Abstract For about two decades, mass customization (MC) is considered as a proper business model for the markets characterized by heterogeneous needs of customers. It can be considered as a win–win strategy that benefits both customers and companies. However, when it comes to environmental impacts of MC, things are less clear and more challenging. This paper aims at investigating how a MC business model performs in terms of environmental sustainability based on an empirical analysis.

Keywords Mass customization · Sustainability · Business model

1 Introduction

From its early introduction as a strategy, mass customization (MC) has changed significantly the market offer and the value proposition for customers. The concept of MC is based on the fact that customers like to be treated as individuals and want to be felt important. They do not want to be involved only in purchasing process, but they tend to be a part of an experience while buying a product [7]. Meanwhile, customers are more concerned about design, esthetic, function, and other attributes of the product and they want to be involved in design process [3]. From the

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companies' perspective, MC acts as an economically viable strategy for the companies. Pursuing MC enables companies to provide their customers with personalized shoes which are produced with near-to-mass production efficiency [14]. MC generates benefits for both company and customers. It enables companies to follow emerging customer trends and bring value to them so that they can be a source of profit generation for the company. It gives customers the feeling of being important and the excitement of being a part of an experience by co-design while providing them with a limited variety that facilitates the purchasing process [5, 8, 13]. MC can also enhance the level of satisfaction of design-sensitive customers by giving them the opportunity to design their own product. However, like any other strategy, the concept of MC has its own pros and cons.

At a first glance, the term MC itself looks like an oxymoron. Combining the attributes of personalization with mass production to offer customized products to mass market, at the beginning, seemed to be more an abstract concept rather than a practical one. However, during last two decades, numerous studies have been carried out to introduce operational and technological enablers for MC, and accordingly now, it has become a trend followed by many companies in different sectors. However, a satisfactory performance of a firm in terms of MC does not necessarily guarantee its success. Emergence of other trends, such as sustainability, within both market and industry, obliges the companies to integrate them with their current strategies and to come out with a business model to enhance the performance of the firm in different perspectives. In this regard, currently, customers' demands for more environmentally friendly products on one hand and tough regulations by governments on the other hand bring out the concept of sustainability as a point of attention for companies. Accordingly, a MC company, like any other company, should monitor and improve its sustainability performance. However, when it comes to environmental impacts of MC, things are less clear and get more challenging. In fact, how MC affects sustainability in a firm is still an open debate. Although in very recent publications there have been debates in this regard [1, 2] and proposals of models to integrate MC and sustainability [4], the discussion is still open since there are very few studies investigating the problem in depth and for specific industries.

This paper aims at targeting this challenge to find out whether a MC business model can be sustainable or not. In other words, can the term "sustainable mass customization (SMC)" be considered as a future business model for MC companies or it is only an oxymoron. We tried to find out the answer by investigating the possible environmental impacts of a MC business model in footwear industry. At first, we propose a MC business model based on both theoretical and empirical data. In next step, we evaluate the sustainability performance of the proposed MC business model throughout two surveys. Finally, we propose a list of possible and potential impacts of several MC enablers, mentioned in the proposed MC business model, based on a set of sustainability key performance indicators (KPI).

2 Development of a Mass Customization Business Model

Designing a business model is a challenging task. It does not only requires a fitting structure which can connect all the parts of business together, but most importantly, it requires a clear view of what one means by "business model." Without knowing the objective of a business model and its specific definition, it is impossible to build an effective business model for a company. We define the term "business model" in this study as a tool containing a set of strategic choices, alternatives, and guidelines to support a company to create, deliver, and capture different forms of value within a value network. It describes how a company can reach its strategic objectives which have been set based on the main strategy of the firm.

Accordingly to implement MC, a company needs to modify the as is business model based on the requirements of MC as a strategy. Development of a MC business model depends upon the definition of its structure and building blocks. The structure of a BM describes its boundaries and illustrates the areas that will be studied more in detail during BM development process. The reference structure applied in this study is the one proposed by Osterwlader and Pigneur [6] (called business model canvas) with minor modifications in order to adopt it to the context of interest. The initial business model canvas of Osterwlader and Pigneur includes 9 building blocks that can be logically grouped into three areas: Left side relates to efficiency (key partners, key activities, key resources, and cost structure), the right side relates to value delivery (customer segment, customer relationship, channels, and revenue streams), and finally the value proposition which is in between. The proposed change is to merge the blocks of cost and revenue into a single block called performance. This is mainly due to the fact that in a MC business, not only cost and revenue are considered as critical issues but also evaluation of customization and efficiency level of the firm is important [10]. Figure 1 illustrates the structure of MC business model.

In next step, the contents of each building block need to be defined. Each block should introduce a set of enablers that facilitate and support the implementation of MC. Therefore, the final developed MC business model can be considered as a library of MC enablers. Identification of these enablers is based on both theoretical and empirical data. Theoretical data are collected by an extensive literature review. In order to collect the theoretical data, a total number of 142 studies published in books, journals, and proceedings during the period of 1996–2012 were reviewed. Empirical data are collected by analyzing five MC footwear companies as case studies. The analysis comprehends both cases of small–medium companies and large companies. Data were collected through different primary and secondary sources including questionnaire, personal interview, papers, releases, and publications on scientific magazines, official company Web site, official financial reports, blogs, forums, communities, and online sector magazine release [10]. Table 1 reflects a summary of analyzed case studies.

As a result, a set of enablers and objectives for MC was identified for each block of business model. Figure 2 shows the final MC business model containing MC enablers.

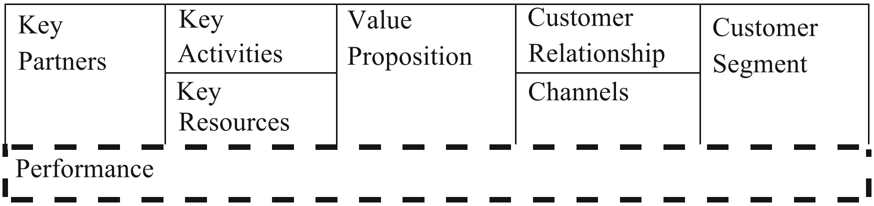

Fig. 1 MC business model structure

Table 1 Analyzed case studies

Company	Country	Foundation year	Size	Mass production beside MC	Type of shoes
A	Germany	1924	Large	Yes	Sport
B	USA	1978	Large	Yes	Sport
C	Brazil	2011	SME	No	Sneakers
D	Germany	2001	SME	No	Classic
E	Australia	2009	SME	No	Classic

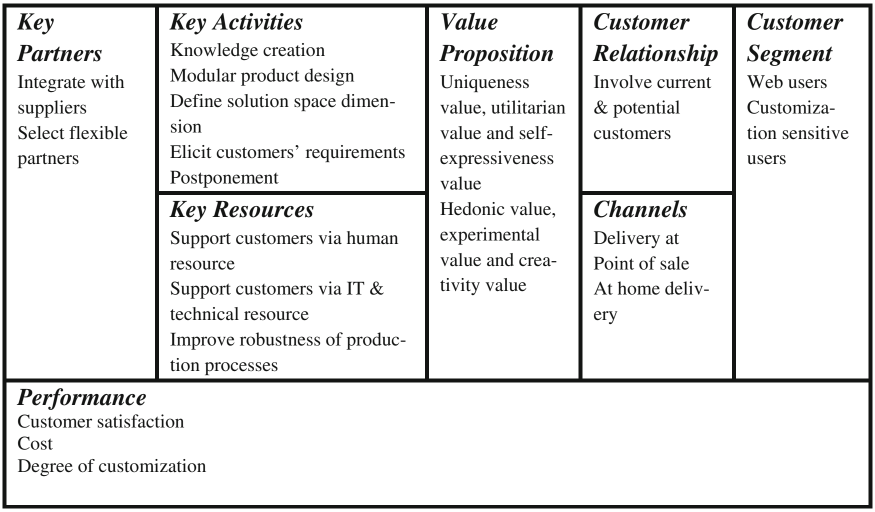

Fig. 2 Developed MC business model

3 Environmental Impacts of a MC Business Model

Development of a MC business model provides the required backbone to analyze the environmental impacts of such a BM. In other words, we can monitor the performance of the MC business model in terms of environmental sustainability to understand "Is mass customization sustainable?" In order to track the possible impacts, three KPI are defined in this study: waste production, energy consumption, and emission. Waste production describes the amount of produced waste during the whole life cycle of the product. Energy consumption relates to the amount of used energy during the whole life cycle of the product. Finally emission describes the amount of green house gas emission during the whole life cycle of the product. Accordingly to evaluate the sustainability influences of MC, we analyzed the impact of each MC enabler presented in the proposed business model on each of three sustainability KPIs.

3.1 Data Collection

In order to collect data, two surveys were designed and sent to two different target groups. One survey was designed to target MC experts in academia and the other to target MC footwear companies. The first survey was sent to 164 academia experts at universities and research centers, and the second one was sent to 35 MC footwear companies. In both surveys, the respondents were asked to identify the possible impacts of 13 selected MC enablers on each sustainability KPI. The total number of MC enablers used in surveys was reduced to 13 since enablers related to the blocks of customer segment, value proposition, and performance are not relevant to the concept of sustainability.

3.2 Data Analysis

Collected data from both surveys were analyzed using a descriptive approach. This was due to the fact that since there was no dependent variable in the data set, an economic approach was not considered as a proper method for data analysis. Figure 3 illustrates a general picture of data analysis. It embodies the statistical distribution of participants' answers regarding the possible environmental impacts of each MC enabler. Each figure relates to one of the sustainability KPIs. To understand the impact of each MC objective on each MC KPI, It is necessary to find the central tendency of the data for each variable. There are usually three main measurement methods to find the central tendency: mean, median, and mode. These measures are used to focus on where the data are clustered or centered. Taking into account that our data set contained discrete data, the mode was the most appropriate method to discover the central tendency.

Analysis of the mode of data for each MC enabler led us to highlight its possible impact on the specific sustainability KPIs. In cases where data show more than one mode, all of them were considered as the possible impact. Table 2 depicts a summary of the results of data analysis.

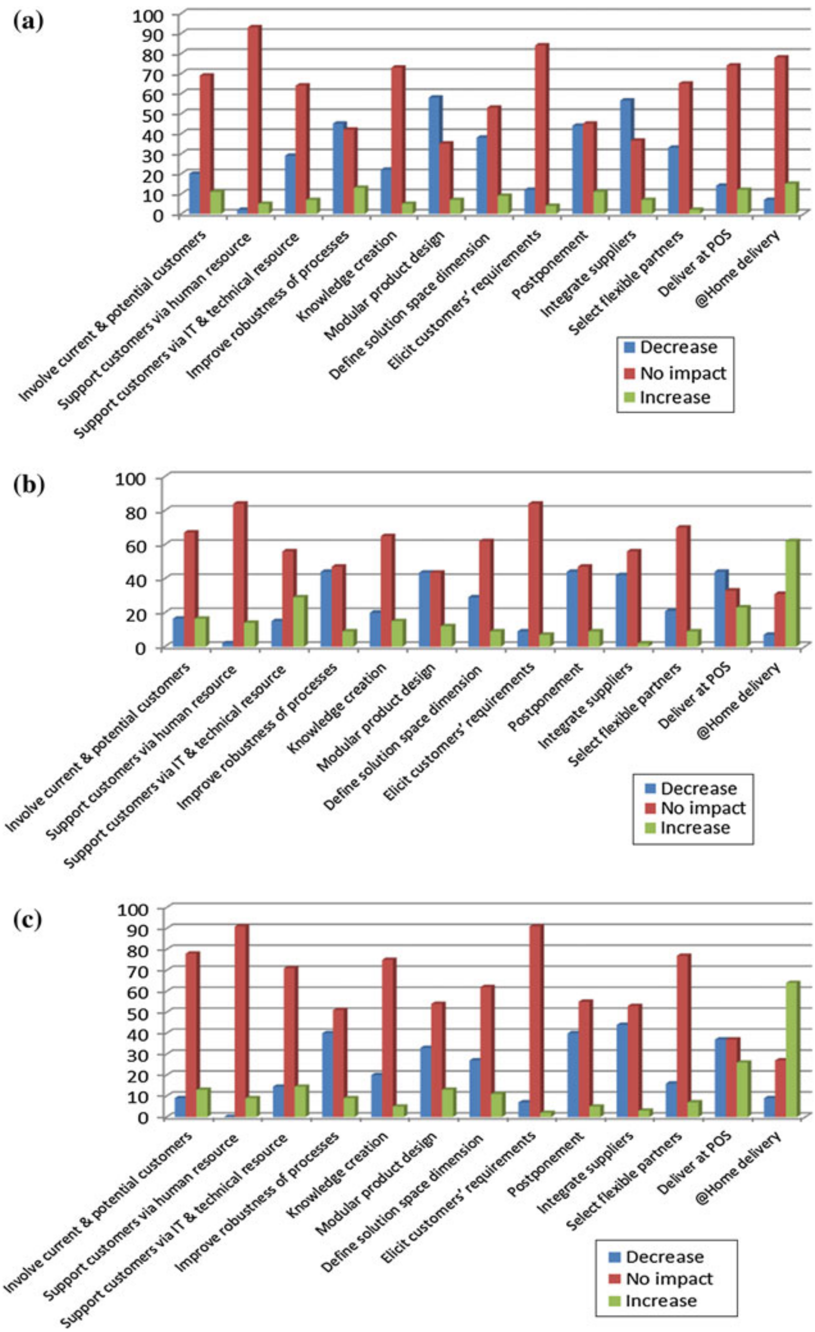

Fig. 3 **a** Data distribution for impact of MC enablers on "waste production," **b** data distribution for impact of MC enablers on "energy consumption," and **c** data distribution for impact of MC enablers on "emission."

Table 2 Impacts of MC enablers on sustainability KPIs

MC Enabler	Impact on sustainability KPI		
Name	Waste production	Energy consumption	Emission
Involve current and potential customers	None	None	None
Support customers via human resource	None	None	None
Support customers via IT and technical resource	None	None	None
Improve robustness of production processes	**Decrease**	**None**	None
Knowledge creation	None	None	None
Modular product design	Decrease	**Decrease/None**	None
Define solution space dimension	None	None	None
Elicit customers' requirements	None	None	None
Postponement	**None**	**None**	None
Integrate suppliers	Decrease	None	None
Select flexible partners	None	None	None
Deliver at POS	None	Decrease	**Decrease/None**
@Home delivery	None	Increase	Increase

4 Discussion

Table 2 can be seen as a guideline to clarify the environmental impacts of the proposed MC business model and hence support the companies to configure a more eco-friendly MC business model. However, the results of data analysis bring into light some challenges and debates as well. These open issues can shape a part of the future research streams in the field of MC. In this paper, we introduce and discuss about four main areas of challenge for sustainable implication of MC. The environmental impacts of these four MC enablers are bolded in Table 2. Data analysis revealed these enablers as critical mainly based on two reasons: (1) There is more than one mode for data; hence, it is not possible to clarify the dominant environmental impact and (2) Although there is a single data mode, the frequency of one of the other two variables is very close to the frequency of data mode. Clarification of the reasons and initiative behind each challenging area and enabler, however, needs a more focused research and further analysis of each area.

4.1 Robust Production Processes

Robust production processes are widely considered as a main capability for MC [11]; however, the impact of this major MC enabler on sustainability has been always a debate in academia. While some believe that having a robust production process is a driver for an efficient production and hence a lower level of waste [9], still there is no clear insight on how robust production affects sustainability performance. Our data analysis confirms such a problematic challenge. While 45.45 % consider it as a force to reduce waste, 41.82 % do not give it any specific role in terms of waste production. The same scenario holds for energy consumption where 47.27 % believe that robust production processes do not affect the level of energy consumption. In contrast, 43.64 % take it as a driving force to reduce the level of energy consumption. The more interesting outcome regarding this MC enabler relates to distribution of answers in academia and in industry. In academia, the percentage of respondents who consider robust production process as a driving force to decrease waste and energy consumption is equal to those who believe it does not affect any sustainability KPI. However, among industrial participants, the outcome is more concrete, emphasizing on the fact that the majority of practitioners do not consider any role for this enabler in terms of environmental sustainably.

4.2 Modularity

Generally, it is believed that a modular architecture of a product leads to a lower level of waste production [12]. At the end of its life, a modular product can be disassembled and the components can be used for disposal, reassembling, or remanufacturing. Consequently, it is expected that modular products are more environmentally friendly than those products with integrated architecture. Our data analysis confirms this claim since 58.18 % of respondents think that modularity acts as driver to reduce waste. Nevertheless, the confusion is mainly related to how modularity affects the level of energy consumption. Does a modular architecture tends to reduce energy consumption to produce a new product since some modules can be reused or reassembled at the end of life of the product or simply it does not affect it at all? The result of data analysis demonstrates a non-clear response in this regard. Respondents do not have a clear idea and are divided into two equally sized groups: first group believe that modularity reduces the level of energy consumption and the second one does not take it as a driving force. However, the reason for this confusion lies on the responses of MC academia experts. While majority of practitioners believe modularity does not affect the level of energy consumption, the academicians are still not sure about the possible impacts.

4.3 Postponement

Postponement, in any production process, is mainly considered as a way to enhance standardization and hence efficiency of the production line. In such a way, it helps a mass customizer to maintain a certain level of efficiency. On the other hand, implementing postponement implies less customized processes and more standard ones which might also lead to a change in the level of produced waste and consumed energy, as well as the level of emission. Accordingly, postponement should be seen as an enabler, which can enhance the sustainability performance in terms of at least one of the three defined KPIs. Surprisingly, based on the survey results, the majority of participants do not consider any specific relationship between postponement and sustainability. Nevertheless, postponement still is a borderline enabler since the percentage of participants who believe it reduces the level of sustainability is very close to those who take it as a neutral factor. Like the previous cases of robust production process and modularity, such uncertainty derives from academia respondents since the majority of participants from companies did not assign any impact for postponement in terms of sustainability.

4.4 Delivery at Point of Sale

Customized products can be delivered to customers via physical stores or online channels. In the case of physical stores, where customers go to the store to customize and order their individualized product, the final product can be delivered to them at the point of sale. The fact that which type of channel is more eco-friendly is still an issue of debate and doubt. The survey results reveal that the challenge is mainly related to understand how delivery at point of sale affects the level of emission. The distribution of answers reveals two different directions for academia and industry. MC companies believe that delivery at point of sale either increases or does not affect the level of emission. On a completely different direction, MC experts think either it reduces or it does not affect the emission. Such a clear difference of opinion between two groups necessitates a further analysis of this enabler while configuring a SMC business model.

5 Conclusion

From its emergence as a trend, MC has been extensively discussed as a proper and potential business model for heterogeneous markets. In a market that is characterized by high levels of heterogeneity in terms of customers’ requirements and needs, MC can be considered as a win–win strategy that benefits both customers and companies. However, in recent years, the increasing sensitivity to the sustainability performance of the companies is a big challenge for firms, and MC companies are not an exception. In this paper, we tried to target this challenge by analyzing the environmental impacts of a MC business model on footwear industry. The empirical study was based on a data collection and analysis from MC experts in academia and MC footwear companies. The results, however, bring into the light a part of challenges and problems regarding mapping the potential impacts of MC on sustainability. Although a proposal regarding the environmental impacts of several MC enablers on three main sustainability KPI is presented in the paper, there are still doubts and confusions revealed during data analysis. One of the challenges relates to some critical MC enablers that their impact on sustainability KPIs is placed on a borderline position and makes it very difficult to decide about the real impact. In the case of these enablers, we suggest a more detailed analysis since the result and impact might vary from one company to the other. Another challenge derives from the huge gap and difference of opinion between academia and industry. In the case of all critical MC enablers, there was a discrepancy between academicians and practitioners. The undeniable observation is that while academicians usually swing between two possible sustainability impacts for MC enablers, practitioners from industry are more concrete about how MC enablers affect sustainability. The revealed gap between these two groups emphasizes again on the fact that how we see things in an academic environment might be totally different from what happens in reality.

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Living Lab Methodology as an Assessment Tool for Mass Customization

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Abstract Mass customization has been regularly used as a growth strategy during the last decades. The strength of this approach stems from offering products adjusted to customers' individual needs, resulting in added value. The latter resides in the word 'custom,' implying unique and utilitarian products allowing for self-expression of the consumer. Researchers and practitioners however predominantly focused on the company's internal processes to optimize mass customization, often resulting in market failure. As a response, a framework with five factors determining the success of mass customization was developed. Additionally, Living Lab methodologies have been used to improve innovation contexts that were too closed. This paper will fill a gap in the literature by demonstrating that the integration of the five-factor framework in the Living Lab methodology is well suited to determine the possible success or failure of a mass-customized product in the market by means of a single case study.

Keywords Living labs · Open innovation · Mass customization · User involvement · Digital signage

1 Introduction

Companies are investing significant resources (time and money) in finding new products or services that can create value. Ortt and van der Duin [1] define innovation as making a new product or service where the 'new' can be distinguished as follows:

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new to the market, the company, or technology. This clarifies that innovation is a broad concept that can be tackled by using several approaches. In this paper, the focus is on a specific strategy within innovation, namely mass customization. Researchers and practitioners agree that involving users can increase the likelihood of an innovation's success in case of incremental innovation [1, 2]. The European Living Lab movement goes even further and argues that innovation should be user-driven, conducted in real-life environments, and involve different stakeholders [3]. They emerged from innovation contexts that were too closed, often resulting in failed innovations attributed to the lack of end user involvement [4]. A user can be involved in the different stages of the innovation process. The goal of this paper is to determine the potential of the Living Lab approach that has been used in several B2C and B2B innovations, combined with a mass customization framework as an assessment tool [5] to evaluate the products' potential success in the market and optimize accordingly.

2 Mass Customization

Mass production has challenged companies to find new market approaches [2]. One of these was to customize products for specific customer segments. Pine [6] defined mass customization as 'developing, producing, marketing and delivering affordable goods and services with enough variation and customization that nearly everyone finds exactly what they want.' The strategy behind it is aligning a company's products with customer needs. Customization can appear in different degrees from no customization to full customization, varying predefined elements, parameters, etc. to choose from. The level of customization has to be adjusted to the customers' needs. To discover those needs, user research is recommended. In the past, researchers have focused on the factors influencing companies to move from mass production to mass customization [6] and the implementation of mass customization in their strategy [7]. However, there is still a lack of research focusing on the factors determining the success of a mass-customized product in the market. Broekhuizen and Alsem [8] suggested a framework with five factors impacting the success of a mass-customized product, but have not tested it yet. This paper will try to fill this gap, by testing the model, and as such the success of the product, in a Living Lab environment, by means of an in-depth case study. The five determining factors are the following:

1. Customer factors or understanding the customer needs. Companies should analyze whether customers show a need for mass-customized products, meaning whether they want to be involved and are willing to pay a premium price.
2. Product factors will influence the possibilities of mass customization. There are four product factors impacting the success, namely the purchasing frequency, the luxury level of the product, the visibility of the product, and the product adaptability. Purchasing frequency gives the producers the option of learning

from their customers, resulting in a learning relationship that will be difficult to establish for other suppliers. Luxury products are in nature more expensive and will therefore be more likely to be customized than products that fulfill basic needs [6]. Products being displayed publicly are more likely to offer variety in product presentation, and customers will prefer products allowing for self-expression. Finally, product adaptability impacts the costs for the company to customize the product and as such the decision to do so.

3. The market factors exist out of two characteristics influencing the use of mass customization, namely the current level of market variety (product proliferation and competitor analysis) and the willingness and ability to adopt. When market variety is high, customers are often confronted with an abundance of choices, increasing the need for customized products. The higher the adoption level, the higher the need for mass-customized products.
4. The industry factors also influence the likelihood of success, namely the growth of production technology, e-commerce, and the growth of flexible production technology.
5. The organization should be capable of delivering the desired products or services quickly, inexpensively, and via a convenient and enjoyable configuration process.

If these five factors are successful, a company can decide to switch to mass customization and be effective in it. This framework will be researched in a Living Lab environment in order to examine the research question, does a Living Lab allow to grasp the five factors more efficiently and evaluate the potential of mass customization?

3 Living Lab Methodology

Living Lab research is a state-of-the-art methodology aiming at the involvement of end users in the innovation process. Living Labs are experimental platforms where end users can be studied in their everyday context [9]. Living Labs confront (potential) users with (prototypes or demonstrators of) products and/or services in the innovation process [5]. This approach has three main advantages. First, it assists in developing more context-specific insights on development and acceptance processes and especially the interaction between both. Second, these experiments inform us about possible conditions for stimulating the societal and economic embedding of technology. Third, embedding it in real-life situations generates images of potential societal impacts of innovation [10]. Living Labs illustrate that users not only initiate the process of innovation, but can dominate the subsequent phases of product development as well [5]. Therefore, this method seems appropriate to research the success factors of a mass-customized product.

Pierson and Lievens [11] identified five stages in the process configuration of Living Lab research. The case study follows those stages to test the possible success of a (new) product going from full customization to tailored customization.

1. Contextualization is an exploratory phase. Different research methods are applied to provide the required background and insights. The contextualization allows us to define the selection criteria and profiles of end users.
2. Selection is the identification and selection of users that will be involved in the Living Lab research. In the selection phase, non-probability sampling is used, such as maximum variation based on sociodemographic variables or criterion sampling trying to understand the different factors and their configuration.
3. Concretization is the initial measurement of the selected users before the technology or service is introduced. Specific characteristics of the users are measured such as their behavior and perception on the technology.
4. Implementation is the operationally running test phase of the Living Lab. There are two major research methods being used: direct analysis by registering user actions remotely (e.g., logging) or indirect analysis by researching the motivations via focus groups, interviews, and self-reporting techniques.
5. Feedback happens at the end of the Living Lab. It exists out of an ex-post-measurement detecting evolutions in the perception and attitudes toward the introduced technology or service. Additionally, technological recommendations are deduced from the implementation phase.

Each of those five stages allows the focus on different success factors, and therefore, a Living Lab appears the most appropriate method to test the mass customization framework and optimize the product of the case study, digital signage content feeds, accordingly.

4 Methodology

The in-depth case study involves a company that recently launched an online platform delivering digital signage content feeds. The idea came from the owners' previous experience in the creation of fully customized content. The company detected a common problem for all users, namely not knowing which content to select. Therefore, they decided to offer more standardized quality content, useful in various situations such as point of sale, point of wait, and point of transit and easy to integrate in the existing content playlist. The aim of the study was to test the readiness of the product for market launch in Benelux and optimize the product accordingly. In this case study, we will look at the potential of using the Living Lab methodology as a research tool for identifying the potential success of a mass-customized product. Case studies can help to understand complex issues or add strength to existing theories. Additionally, they are the most commonly used method for researching technology adoption at an organizational level [12].

Considering the mass customization model of Broekhuizen and Alsem [8] has not been implemented in practice yet and the Living Lab method requires a natural setting [4], a combination of both discussed frameworks seemed the most appropriate for this research. A Living Lab approach offers the possibility of iteratively optimizing a product. After each step, the company involved can improve their product, organization, strategy, etc. based on the results of the Living Lab building block. Therefore, it appears to serve as a perfect tool to prepare for launching a mass-customized product in the market. The different success factors of mass customization were integrated in the building blocks of the Living Lab methodology. The table gives an overview of the different phases of the Living Lab evaluating the different success factors of mass customization. This paper will only discuss the first three phases and its results because the Living Lab case is still in progress.

The research flow is visualized in Table 1.

4.1 Contextualization

During a start-up session, a first scan of the market, the product, and the organization was established. The value proposition canvas, a tool to detect the supposed added value for your (future) customers, was filled in together with the supplier of digital signage content feeds. The value proposition is created through usage of the product/service, reduction in customer risks, or the efforts a customer has to make. The concept of mass customization allows a company to integrate an extra value to the customer by allowing them to personalize and configure their value package. In other words, the customer is involved in the value creation process [13]. Additionally, the researchers conducted desk research to generate some first impressions on the product/market fit by scanning the market, competitors, and its environment.

4.2 Selection

In B2B research, the importance of the market structure prevails [14], meaning the different stakeholders and their potential to influence the product's potential need to be uncovered. Eight stakeholders were selected and interviewed, each varying in their level of involvement with digital signage content, namely operational work area, containing businesses and the wider environment [15]. This is a major difference with Living Lab research in a B2C environment where the focus is often purely on the involvement of end users. The Table 2 shows the stakeholder model for digital signage content.

Table 1 Research flow based on [8, 11]

	Pre			Intervention	Post
Living lab methodology	Contextualization Secondary research of customer product market industry organization	Selection Selection of stakeholders	Concretization Expert interviews: evaluation of first ideas	Implementation Business workshop: co-creation and optimization of the product	Feedback Evaluating evolutions in perceptions
Mass customization success factors	Research focus: customer, product, market, industry, and organizational factors	Research focus: customer factors	Research focus: customer, product, market, and industry factors	Research focus: customer, market, and product factors	Research focus: customer, market, and product factors

Table 2 Stakeholders involved in the living lab

Digital signage owner	Software and content management solutions provider	Integrator and hardware	Consultant
$N = 2$	$N = 2$	$N = 2$	$N = 2$

4.3 Concretization

By organizing face-to-face interviews with these different stakeholders, located in different areas of Belgium, we gained more in-depth knowledge of digital signage content, its market, and customer needs.

5 Results

During the first three phases of the Living Lab, an evaluation of the five factors of the mass customization framework was established. In the contextualization phase, the value proposition canvas and desk research showed that the digital signage industry is in a mature stage when it comes to technology. There have been some major advances in resolution, and costs have been reduced significantly. As such, most businesses can now afford the hardware for digital signage. Therefore, a next important issue arises: designing an appealing and conveying message that engages customers. Digital signage content providers will become more important allowing for different levels of customization and delivering a design that fits the company's image. The company being researched is capable of delivering that desired content quickly, efficiently, and inexpensively by means of the content feeds. Additionally, digital content is visible to a company's customers and requires the possibility to adapt it to the company's wishes. Therefore, the need to customize digital signage content arises. In other words, the industry, product, and organization seem ready for mass customization. Nevertheless, the current Belgian market variety seems limited compared to the world and consequently the market might not be willing to accept the product yet. Additionally, the customer needs are not clear for the Belgian market. Previous research has focused more on international needs and less on region-specific needs. Insights into the Belgian customers will be required. The results of the contextualization phase indicated the need to interview different stakeholders in order to gain deeper understandings of the market and customer needs.

When analyzing the concretization phase, we noticed that the new product has its limitations. Although the product itself is perceived as attractive, efficient, and qualitative, it does not satisfy the customers' needs completely. They show that the product will have to offer more variety, and it appears too standardized on the customization ladder. More parameters will have to be added to the current offer in order to better fulfill customer needs. Additionally, the product does not fit into the

Benelux market structure and value chain of digital signage. The market used to be cluttered and is slowly consolidating, resulting in an interconnected market with some bigger players. As some of the stakeholders perceive the product as an intruder in the market, it will be hard for the company to launch the product. The integration of the content feeds is not always supported by their hardware and software, meaning it needs to move away from its current coding structure. Additionally, customers buy their content together with their hardware and software offered by system integrators, which makes it difficult to operate as content provider without integrating other services. In other words, the company will have to fulfill more customer and system integrator needs, change the product and their organizational strategy in order to make their product successful. The advantage of iterating during the Living Lab before continuing the following steps appears to be a useful strategy for the introduction of a mass-customized product in the market. The results allowed the company to change course and optimize the product to better suit its customers' needs. In a next phase, the intervention phase, a business workshop will be organized with the different stakeholders involved to optimize the product even further and influence the market factors where possible. Additionally, the opportunity will arise to test whether the optimization was successful and to decide upon their market and organizational strategy from there. In a following stage, the feedback phase, a final evaluation of the product will happen.

6 Conclusion

The results of this study imply a working method to identify the potential success of a mass-customized product. Researchers and practitioners from different industries can implement the Living Lab methodology to study the different success criteria of a mass-customized product and iterate accordingly. It can be applied for incremental as well as radical innovations. The mass customization framework appears effective in analyzing the potential of a mass-customized product, especially because it focuses on more than internal processes and additionally involves external factors such as the market and the customer. It allows managers to use it as a structure to identify and found their strategy of mass customization on. The advantage of using it in a Living Lab environment is the possibility to iterate when the product does not appear market ready and to optimize the different factors by involving a diversity of stakeholders in a real-life environment. The involvement of multiple stakeholders and of the end users allows for multiple perspectives and angles to be taken into account when evaluating the success factors. The framework contributes by structuring the Living Lab approach even further. Both strengthen each other and the results of the research.

Considering mass customization is a form of innovation, future research should focus on the applicability of the framework within a Living Lab environment for other sorts of innovations.

Although only the prephase of the Living Lab was performed, we believe that the next phases will only add value to the current results and allow for further product optimization. Considering this research is work in progress, we will be able to follow up on the potential of the other phases of the Living Lab and their applicability in determining the success of a mass-customized product.

Performing user research within a B2B context is a challenge. The heterogeneity of businesses prevails, and as such, the selection process of users becomes more difficult. Therefore, the contextualization and selection phases of the Living Lab become more important. Defining the market structure with its different stakeholders is a first step in this process. If a mass-customized product will be tested for the B2C market, the focus should be more on the end users compared to multiple stakeholders. Previous Living Lab research has mainly focused on B2C Living Labs, and as such, the findings of this Living Lab case can serve as input on how to implement the Living Lab methodology in a B2B environment.

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Managing Process Customisation for the Capital Goods Sector: An Application Case Study

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Abstract The capital goods sector is characterised by a limited number of large orders with a high degree of customisation. This means neither products nor processes are standardised, making it difficult to accurately determine delivery times, often resulting in non-fulfilment. This paper describes a conceptual model used in a methodology for defining a reliable production system regarding both delivery times and cost, enabling companies to reach achievable commitments with customers and improve their responsiveness to major changes in demand. This model is based on defining and scheduling generic assembly processes that can be customised for each particular order. The description of the conceptual model is illustrated by an application case study at a hydraulic presses manufacturer.

Keywords Capital goods · Mass customisation · Generic processes · Lean production · Just-in-time (JIT) · Value stream mapping (VSM) · Takt time · Pull systems

1 Introduction

The capital goods sector is characterised by a limited number of large orders, with major fluctuations in the order backlog, which leads to different production areas having a highly variable workload. Also, these orders have a high degree of customisation, in order to fulfil customer requirements. The consequences of this are as follows:

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- Because products are not standard, the process is longer. Specific machine design stage and an adjustment stage at the end of the machine assembly are required, and the process is longer. Also, having no standard products means component purchasing cannot be done before the orders arrive.
- Because processes are not standard, the delivery times are uncertain, and the companies often fail to fulfil them.

In order to minimise the effects of the latter point, capital goods sector companies need a reliable production system that will allow them to make and meet achievable commitments to their customers. Companies would therefore be able to fulfil these commitments with no risk of penalties, improving their market image and controlling their operating margins.

Over the last few years, companies offering customised products and services have begun to use mass customisation (MC) as a strategy for achieving a competitive edge [1].

Concepts such as customer-driven, flexible, lean manufacturing [2] and just-in-time (JIT) manufacturing have appeared on the MC scene as strategies for achieving efficiency levels close to those of mass production [3–5].

These productive approaches have been widely used by mass production companies, but they have been of little use in high-variability/low-volume environments such as the capital goods sector. It has even been questioned whether or not lean manufacturing techniques should be used in these environments [6], although there have been cases of application in custom manufacturing industries, e.g. in the aerospace [7], naval [8] and machine tool [9] sectors.

Although the production approaches mentioned are not directly applicable to the capital goods sector, some of their concepts, together with value stream mapping (VSM) [10], a tool used in lean manufacturing to analyse the material and information flows required to make a product or service available to customers, may be adapted and applied to defining and implementing a reliable production system for companies in this sector.

Taking these concepts into account (takt time, flow, pull systems, etc.), IK4-IKERLAN has developed a methodology for defining a reliable production system that will enable capital goods sector companies to make and meet achievable commitments to their customers. The key component of this methodology is a conceptual model, presented in this paper, along with its application at a stamping press manufacturing company.

The outline of this paper is organised as follows: Sect. 2 describes the research approach. In Sect. 3, some characteristics of capital goods sector are presented. Sections 4 and 5 present the conceptual model on which the proposed production system is based and the application case. In Sect. 6, some conclusions are presented. Finally, Sect. 7 sets out some future lines of work.

2 Research Approach

We present an application case study, based on the results of an applied research project. This project resulted in the definition of a methodology for designing and implementing a production system at capital goods sector companies that will enable a regular assembly pace (takt time) and synchronising the other order cycle activities (design, purchasing, etc.) with this pace.

This methodology was later applied at several capital goods sector companies, to validate both the suitability of the methodology and the conceptual model included in this methodology. This paper describes one of these application cases.

3 Sector Scenario

Projects at capital goods sector companies tend to be highly customised. This makes it impossible to standardise products (except for commercial items and auxiliary elements), as each product is new. As practically no stocking can be done, purchasing lead times interferes with delivery times and project planning.

Normally, project planning is not detailed enough, as there are no standard processes (the projects are always different). Due to there is no a detailed scheduling, the purchasing department does not know the exact date on which the materials will be required, and the technical office does not know the exact dates on which designs will be required, so deadlines for obtaining project requirements are not known either.

Also, when the machine assembly needs to be rescheduled for any reason (problems with the current project and/or with other projects running in the assembly plant), the initial planning is no longer valid and all dates should be calculated again, which does not always happen, resulting in wrong information being used and a total loss of control over what is occurring in each project and in the shop floor.

The 'push system' is therefore used for project management, to forestall problems whenever possible—the sooner the work is done, the better.

So, for the first part of the project (requirements, design and initial purchasing), there is no pressure, as regards delivery dates, as all those involved know, are normally tentative, and the deadline pressure therefore shifts to the second part of the project (assembly and adjustment stages), meaning overtime, pressure on suppliers, extra costs due to rush deliveries, adjustment work done only partially or not at all, assembly processes postponed until final assembly at the customer's facilities, etc.

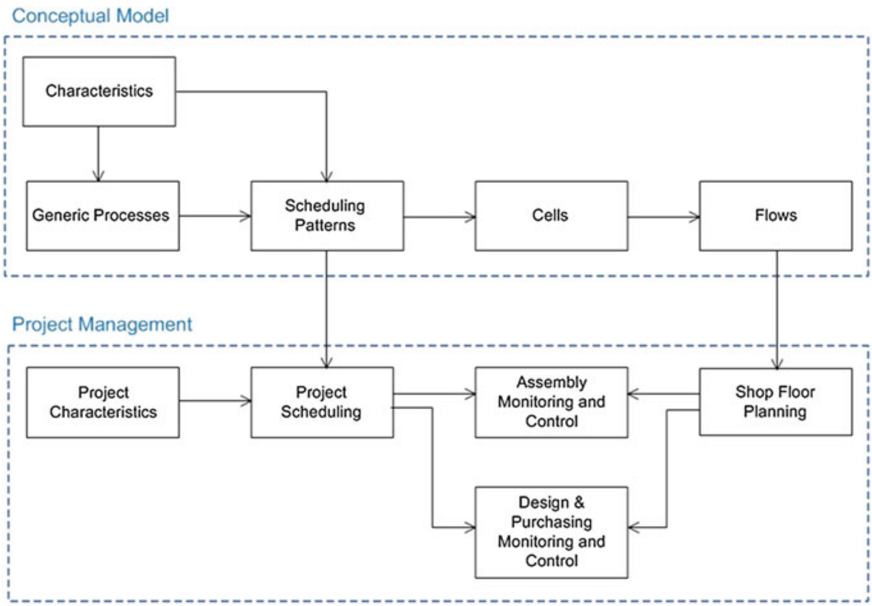


Fig. 1 Production system

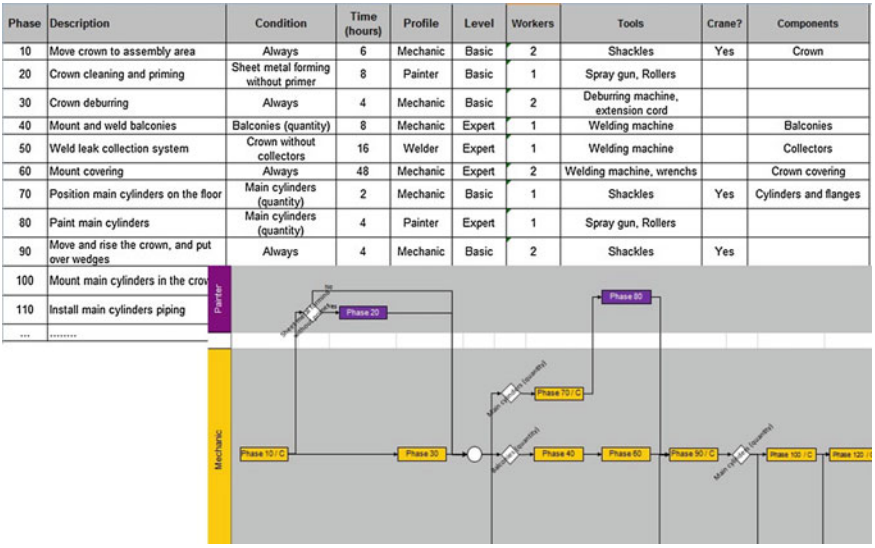
4 Production System Proposed

It is true to say that it is not possible to fully standardise products and production processes at capital goods sector companies, *but easily customisable generic products and processes can be defined to a large extent*, because, although all projects may be different, many of them have similarities.

Taking this premise as a starting point and focusing on production processes, the developed methodology is used to define a production system for predictably and orderly assembling, adjusting and disassembling of machines, guaranteeing the delivery deadlines, achieving a good capacity utilisation of productive resources and working in accordance with the shop floor's limitations.

The production system is based on a network of cells that is organised by products, synchronised according to a particular pace (takt time), easy to schedule and with guaranteed performance.

This system (Fig. 1) is defined on the basis of a conceptual model with four main blocks: generic processes, scheduling patterns, cells and flows. Once the information on these blocks has been defined, for each project, depending on its characteristics, the customised scheduling for the cells can be obtained, together with the information required for the project monitoring and control.



Phase	Description	Condition	Time (hours)	Profile	Level	Workers	Tools	Crane?	Components
10	Move crown to assembly area	Always	6	Mechanic	Basic	2	Shackles	Yes	Crown
20	Crown cleaning and priming	Sheet metal forming without primer	8	Painter	Basic	1	Spray gun, Rollers		
30	Crown deburring	Always	4	Mechanic	Basic	2	Deburring machine, extension cord		
40	Mount and weld balconies	Balconies (quantity)	8	Mechanic	Expert	1	Welding machine		Balconies
50	Weld leak collection system	Crown without collectors	16	Welder	Expert	1	Welding machine		Collectors
60	Mount covering	Always	48	Mechanic	Expert	2	Welding machine, wrenchs		Crown covering
70	Position main cylinders on the floor	Main cylinders (quantity)	2	Mechanic	Basic	1	Shackles	Yes	Cylinders and flanges
80	Paint main cylinders	Main cylinders (quantity)	4	Painter	Expert	1	Spray gun, Rollers		
90	Move and rise the crown, and put over wedges	Always	4	Mechanic	Basic	2	Shackles	Yes	
100	Mount main cylinders in the crov								
110	Install main cylinders piping								
...	....								

Fig. 2 Generic process

4.1 Conceptual Model

The **processes** defined in this conceptual model are generic and therefore are not related to a specific machine but to an entire family of machines.

Each process (Fig. 2) consists of a set of phases or operations which need to be carried out, predictably and following a sequence, established in a precedence diagram, for assembling a component, assembling a machine, adjusting it, etc. Each phase of a specific project will be carried out if its condition, defined on the basis of the machine's characteristics, is fulfilled.

To carry out the projects, first they must be scheduled. For quick and efficient scheduling, a set of **scheduling patterns** (Fig. 3) have been defined, which can be customised for each new project as required, so each machine does not have to be scheduled from scratch.

Each pattern consists of one or more processes, with the detailed scheduling of a part of a 'mock' machine, taking into account the most common values for the characteristics of the machine, and the resources available (workers, number of shifts) for carrying out the project, which will determine the pace (takt time).

A **cell** is a set of resources (workers, tools, etc.) work within a specific environment and that are able to put a set of scheduling patterns into practice within a guaranteed period of time. It is essential to guarantee the pace of each cell. Therefore, decisions to minimise arising problems need to be taken, in order to solve them by the deadline established, whenever possible. For this reason, workers should not be given an excessive workload (below 85–90 %).

											W1					W2		
Code	Phase Description	Condition	Condition Value	Profile	Level	Worker	Shift	Hours T	Hours to Schedule	Hours Scheduled	D1	D2	D3	D4	D5	D1	D2	D3
Crown-10	Move crown to assembly area	Always	1	Mecanic	Basic	Mecanic 1	M	6	6	3	3							
Crown-010	Move crown to assembly area	Always	1	Mecanic	Basic	Mecanic 2	M			3	3							
Crown-020	Crown cleaning and priming	Sheet metal formind without primer	0	Painter	Basic			8										
Crown-030	Crown deburring	Always	1	Mecanic	Basic	Mecanic 1	M	4	4	4	4							
Crown-040	Mount and weld balconies	Balconies (quantity)	1	Mecanic	Expert	Mecanic 1	M	8	8	8		8						
Crown-050	Weld leak collection system	Crown without collectors	1	Welder	Expert	Welder	M	16	16	16		8	8					
Crown-060	Mount covering	Always	1	Mecanic	Expert	Mecanic 1	M	48	48	24			8	8	8			
Crown-060	Mount covering	Always	1	Mecanic	Expert	Mecanic 2	M			24			8	8	8			
Crown-070	Position main cylinders on the floor	Main cylinders (quantity)	3	Mecanic	Basic	Mecanic 2	M	2	6	6		6						
Crown-080	Paint main cylinders	Main cylinders (quantity)	3	Painter	Expert	Painter	M	4	12	12			8	4				
Crown-090	Move and rise the crown, and put over wedges	Always	1	Mecanic	Basic	Mecanic 1	M	4	4	2						2		
Crown-090	Move and rise the crown, and put over wedges	Always	1	Mecanic	Basic	Mecanic 2	M			2						2		
Crown-100	Mount main cylinders in the crown	Main cylinders (quantity)	3	Mecanic	Expert	Mecanic 1	M	2	6	6						6		
Crown-110	Install main cylinders piping	Main cylinders (quantity)	3	Hydro-pneumatic	Expert	H-Pn 1	M	4	12	6						6		
Crown-110	Install main cylinders piping	Main cylinders (quantity)	3	Hydro-pneumatic	Expert	H-Pn 2	M			6						6		
....	......	....	....	....	....	....	....	....										
									122	122								

					W1					W2		
Hours/Week	Saturation	Hours	Worker		D1	D2	D3	D4	D5	D1	D2	D3
40	24%	47	Mecanic 1	M	7	8	8	8	8	8		
40	18%	35	Mecanic 2	M	3	6	8	8	8	2		
40	3%	6	H-Pn 1	M						6		
40	3%	6	H-Pn 2	M						6		
40	8%	16	Welder	M		8	8					
40	6%	12	Painter	M			8	4				

Fig. 3 Scheduling pattern

Finally, define **flows** involves dividing the shop floor layout into 'assembly lines', according to the product mix expected to be sold in the next months or years. An 'assembly line' is taken to mean a specific path where a set of cells, synchronised according to the takt time, are used to assemble machines of a specific type.

4.2 Project Management

The **project** is **scheduled** by choosing suitable scheduling patterns. The pattern scheduling is customised according to the machine characteristics for the project, maintaining the phases required for the project, deleting those that do not form part of it and scheduling any required phases that are not scheduled in the pattern. Finally, the customised scheduling is adapted to the project, balancing the workload of assembly workers.

For **project monitoring,** the information required is prepared based on the project scheduling and the shop floor planning. During assembly monitoring and control, periodically (e.g. weekly), the fulfilment of each process phase is checked.

On the other hand, the detailed scheduling for each machine indicates which materials, and when, are needed for assembling each module and the whole machine. Knowing the materials' delivery time, the deadline for order release is known, and this will also be the deadline for completing the corresponding design.

Fig. 4 A hydraulic press

5 Application Case

5.1 The Company: Product and Stages of a Project

The case study company is ONAPRES, one of the most important European designers and manufacturers of hydraulic presses (Fig. 4). It custom-manufactures all its presses for each customer, always considering their needs a top priority.

Recently, ONAPRES and FAGOR ARRASATE, a world leader in the design, manufacturing and supply of presses and stamping systems, metal cutting and processing lines, have announced the full merge of their activities creating together the company worldwide with the broadest catalogue of solutions for the sheet metal forming and processing sectors.

Concerning product families, its highest percentage of sales is in modular frame presses, followed by monoblock presses. Other press families (column presses, hot drape forming machines, special presses) represent only a minor percentage. We therefore chose the modular frame and monoblock press families for the case study. The major modules for both types of presses are shown in Table 1.

Table 1 Major modules of presses

	Modular frame presses	Monoblock presses
Crown	x	
Slide	x	x
Upper cushion	x	x
Uprights	x	
Moving bolster	x	x
Lower cushion	x	x
Bed	x	
Monoblock frame		x

The stages of a typical project for this company are as follows:

- When the order is placed, the company's technical manager gathers all order requirements, with collaboration from the commercial department.
- The technical office creates all the press designs (mechanical, hydraulic, pneumatic, lubrication, electrical, PLC programs, etc.).
- At the purchasing stage, the purchasing department converts the completed designs into material requirements and places purchase orders.
- Suppliers deliver materials to the assembly plant.
- Main press units or modules are then assembled.
- When all modules are finished, the whole press is assembled.
- PLC programs, user interface, etc. are loaded, and the adjustment is made.
- The press is disassembled, and the modules are painted and packaged.
- The modules are dispatched and transported to the customer's facilities.
- The press is assembled again at the customer's facilities and started up.

5.2 Model Defined

In this case, it has been defined 19 *generic processes* and 17 *scheduling patterns*, for the modules' assembly, press assembly, adjustment and disassembly, and painting and packaging, with 125 *characteristics* for customising processes. These processes and patterns are grouped according to the type of modules and presses. Table 2 shows the relationship between them (in parentheses, the number of processes or patterns for each group and the average number of phases or operations for each one).

Also, it has been defined four types of cells. Each one can perform one type of scheduling patterns (B, C, PA&A and DP&P) and requires a certain space to perform its tasks. In this case, in the shop floor, there are 6 assembly areas for heavy modules ('H') and 9 assembly areas for light modules ('L'). There is also a pit in which 3 presses can be assembled simultaneously. The cells have been configured as shown in Table 3.

Table 2 Relationship between generic processes and scheduling patterns

		Scheduling patterns							
		Modular frame presses				Monoblock presses			
		B (2 patterns/ 176 phases)	C (3 patterns/ 147 phases)	PA&A (6 patterns/ 136 phases)	DP&P (2 patterns/ 136 phases)	B (1 patterns/ 140 phases)	C (1 patterns/ 89 phases)	PA&A (1 patterns/ 134 phases)	DP&P (1 patterns/ 54 phases)
Generic processes	Bed (1 process/90 phases)	X							
	Uprights (2 process/27 phases)	X							
	Monoblock frame (1 process/75 phases)					X			
	Moving bolster (1 process/35 phases)	X				X			
	Lower cushion (1 process/20 phases)	X				X			
	Crown (1 process/54 phases)		X						
	Slide (1 process/55 phases)		X				X		
	upper cushion (1 process/20 phases)		X				X		
	Press assembly (1 process/43 phases)			X				X	
	Adjustment (1 process/71 phases)			X				X	
	Disassembly, painting and packaging (1 process/103 phases)				X				X

Table 3 Cells

Cell	Modular frame presses		Monoblock presses	
	Modules/tasks	Areas	Modules/tasks	Areas
B	Bed, moving bolster, lower cushion and uprights	2 H + 1 L	Monoblock frame, moving bolster and lower cushion	1 H + 1 L
C	Crown, slide and upper cushion	1 H + 1 L	Slide and upper cushion	1 L
PA&A	Press assembly and adjustment	1 pit	Press assembly and adjustment	1 pit
DP&P	Disassembly, painting and packaging	1 pit + 3 H + 5 L	Disassembly, painting and packaging	1 pit + 1 H + 1 L

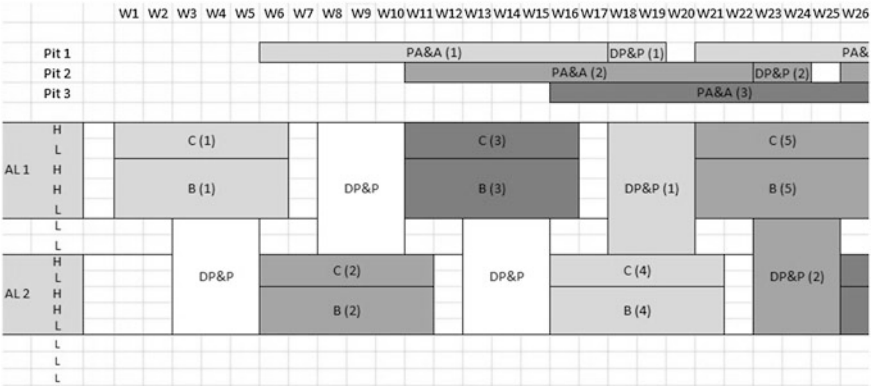


Fig. 5 Modular frame presses distribution

Taking into account the areas needed by each cell, the layout of the shop floor is organised in two assembly lines.

Finally, organise flows, as said before, consist in select the set of cells needed to carry out each project and place these cells into an assembly line. In Fig. 5, as an example, several modular presses have been distributed (synchronised) into the two assembly lines defined.

For the synchronisation of presses in the different assembly lines, the bottleneck must be taken into account. In this case, the bottleneck occurs during the disassembly of modular frame presses, due to the assembly areas occupied; thus, the presses have been arranged so that two disassembly processes never take place at the same time.

6 Results

In the application case, presented in this paper, the current situation was diagnosed before defining the model. Eight presses were manufactured at the plant in 2011 (six modular frame presses and two monoblock presses), with the shop floor working at practically full capacity. Once the model was established, depending on the product mix, it was concluded that 10 modular frame presses or nine modular frame presses and two monoblock presses could be assembled per year. It has been estimated an increase in productivity between 25 and 37 %.

7 Conclusions

In this paper, we have presented an application case study for a methodology that focuses on the design and implementation of a reliable production system that will enable capital goods sector companies to make and meet achievable commitments to their customers.

Defining a reliable production system using the methodology presented in this paper has the following advantages:

- It facilitates assembly management as detailed scheduling is obtained quickly and easily. The detailed scheduling of the project allows workers to know the tasks they have to perform each day and allows project manager to control accurately the progress of the project.
- It enables maximum productivity to be obtained from the shop floor, optimising bottlenecks.
- It provides an overview of the whole assembly plant.
- It allows sales agents to provide more accurate delivery dates, based on prior knowledge about whether or not the shop floor can respond.
- It guarantees deadlines promised to the customer, eliminating penalties due to delays.
- It shortens deadlines, enhancing the appeal of the commercial offer.

8 Future Research Lines

In the case study presented above, the methodology focused on assembly processes. The next step would be to extend the application to other connected stages of the order cycle such as purchasing and design, so that they are synchronised with the assembly stage and so that assembly requirements, scheduled according to delivery dates, determine the dates on which the work needs to be done for that stages, i.e. a ‘pull system’, with the assembly stage ‘pulling’ the previous stages.

On the other hand, developing a support tool for the methodology to facilitate the tasks of defining and updating information about the blocks of the model would be a significant improvement at both the model definition stage and that of production system operation.

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Mass Customization and Performance Assessment: Overview and Research Directions

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Abstract Mass customization (MC) has been introduced as the future of manufacturing, and great results have been proven. Recent research, however, documents a high failure rate for companies trying to adapt to MC as a business strategy. Making this transition is, as highlighted by several scholars, an enterprise transformation that requires strategic control mechanisms. This paper contributes to existing MC literature with an overview and analysis of available MC performance assessment methods. Shortcomings of the literature are identified and directions for future research given.

Keywords Mass customization · Performance assessment · Literature review performance measurement · Capability assessment

1 Introduction

Based on the increased demand for product customization and intensified competition, manufacturing companies today are required more than ever to deliver product variants in an efficient manner. Mass customization (MC) is a concept and operation strategy embracing different strategies for delivering products that meet individual customers' needs with near mass production efficiency.

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MC arose as a concept in the late 1980s and was popularized in the early 1990s [26]. The concept has been adopted by industry for years, and the body of knowledge on MC has simultaneously grown. A recent study of 500 firms reports, however, a high failure rate at implementing MC, both for company start-ups and established firms. The reasons for this high failure rate are many, pointing in different directions and at different levels.

Research has for years focused on clarifying the fundamental or defining characteristics of firms that successfully adopt the MC strategy. Among other things, this has led to the introduction of three fundamental MC capabilities: solution space development, robust process design, and choice navigation [28]. Several researchers, e.g. [10, 19, 31] have adopted the three fundamental capabilities and continued this line of research, supporting that a more comprehensive understanding of which characterises constitute a successful mass customizer can be developed.

The transition toward MC is as highlighted by several authors, among others Salvador et al. [28], not an isolated activity; it is an enterprise comprising a wide continuous innovation effort involving both radical change and continuous improvement. From this, it is clear that focusing on what characterizes a successful mass customizer is not sufficient guidance for companies to ensure a successful transition. Based on this, we argue that one of the central reasons for the high failure rate in industry is a shortcoming of theory in giving adequate guidance for companies in how to undertake the organizational transition. Many MC researchers have also clearly stated the need for more research addressing the managerial aspects of MC, e.g., [16, 28]. The research on MC has only recently given increased attention to providing knowledge about how to undertake and support the transition toward MC.

The relation between success of improvement in a change process and use of performance measurement and management has been documented in several cases. One example is Kristal et al. [16], who, through data investigation from 167 mid- to large-sized manufacturing plants, prove that the use of feedback information favorably contributes to the development of MC capability. Based on these results, Kristal et al. [16] argue that continuous improvement and performance assessment are key elements for addressing the issue of ensuring a successful MC implementation. Throughout the last decade, the use of performance assessment has gained increasing attention within MC research, e.g., [4, 8, 23, 29] to mention some of the later contributions.

The literature on assessing organizational performance has in general split into two main streams. One stream focuses on metrics, performance measures, performance measurement systems, and approaches to performance management, e.g., [11]. The other stream of the literature, which is primarily found within quality management literature, focuses more on the use of capability maturity frameworks in the assessment of organizational capabilities, e.g., [20].

Based on a coarse literature review in [29], we argue that research on MC seems to speak much about capabilities but little about how to measure them. MC literature addressing performance assessment appears to be unilateral, focusing mostly on performance metrics. Furthermore, the literature offers only a scarce overview of how performance assessment has been addressed within the MC domain. In order to ensure progression on this topic and ultimately to ensure that relevant tools and methods can be developed for guiding companies in their transition toward MC, we see a need for giving an overview of MC research addressing performance assessment.

The purpose of this paper is to review the literature addressing performance assessment within MC, clarify focus, evaluate ability to give relevant feedback information in the organizational change process of implementing MC, identify potential gaps, and, based on this, give direction for future research. The research questions have been framed as follows:

- RQ1: What performance assessment methodologies are available within the domain of MC?
- RQ2: What is the capability of available performance assessment methods in giving guidance to companies in the transition toward MC?

To answer research question 1, the central dimensions along which the available methods are reviewed are introduced in the following section. Based on these, the literature on performance assessment within MC is reviewed in Sect. 3, and, in order to answer research question 2, performance assessment methods are analyzed with a focus on their ability to support the transition toward MC. In closure, the results are discussed, the gap in the current literature is identified, and directions for future research are given.

2 Performance Assessment

In order to provide a valuable overview of the existing literature, a general frame for classifying research on performance assessment is needed. Based on this, the purpose of the following section is to clarify along which dimensions the literature has to be reviewed by looking into the general literature on performance assessment.

It has long been recognized that performance assessment plays an important role in the efficient and effective management of organizations [15]. This topic has, as recognized by Folan and Browne [11], among others, also gained focus in an ever-increasing number of academic fields. Research on performance assessment was initiated in management accounting at the beginning of the twentieth century, and it later gained a broader role in non-financial disciplines, such as operations management, marketing, and human resource management [6]. Organizational performance is by no means a simple phenomenon; rather, it is a complex and multidimensional concept. The purpose of conducting performance assessment is to achieve [21] “closed-loop deployment of organizational strategies, allowing relevant information to feed back to the appropriate points facilitating decision and control processes.”

Assessment of organizational performance has split into two main streams in the literature, providing a relevant dimension for initial classification. One stream focuses on metrics, including performance measures or performance measurement systems. In this stream, performance is typically measured using a quantitative approach and is expressed in figures or by the use of an index, etc. The other stream focuses more on the assessment of organizational capabilities, e.g., through the use of capability maturity frameworks. In this stream, performance is typically evaluated using qualitative approaches.

Another relevant dimension in analyzing the literature on performance assessment is given by Folan and Browne [11], who, based on an extensive literature review, argue that the research on performance measurement gives recommendations on four different levels or dimensions:

1. Individual performance measures.
2. Structural frameworks (set of performance measures).
3. Procedural frameworks (process of building performance measures systems).
4. Performance measurement systems (the integration of the above points).

"Structural performance framework" refers to the set of recommendations, boundaries, dimensions, and relations in between the measures [11]. In addition, performance systems provide guidance for the employment of performance frameworks or particular sets of performance measures. Although the split between the literature addressing performance assessment as individual metrics, measurement frameworks, and measurement systems is only developed within performance measurement, we also find it to be highly relevant within capability assessment.

Based on these two dimensions, the framework depicted in Fig. 1 has been developed for use in the assessment of the available methods.

In addition to the two dimensions depicted in Fig. 1, it is relevant to address the scope of the method, i.e., which of the fundamental capabilities the method gives performance feedback to. Based on this, the literature is reviewed according to the following questions:

- What is the purpose of the method?
- Which type of performance assessment does the method build on?
- At what level are recommendations given?
- In what way is the suggested method given guidance in the transition?
- To which of the fundamental capabilities is the method relevant?

3 Mass Customization and Performance Assessment

With the use of the framework clarified above, the central literature on performance assessment within MC is reviewed in the following. The literature review is done on the basis of an extensive search primarily using the Web of Science

Level of Recommendation / *Focus of recommendations*	**Performance Measurement**	**Capability Assessment**	**Combined**
Individual metrics or capabilities			
Procedural Framework Set of metrics or capabilities, combined			
Structural Framework Set of metrics or capabilities, combined			
System Metrics or capabilities integrated in a framework with procedural guidance			

Fig. 1 Dimensions in the literature review

database. Combined title and topic searches have been conducted using combinations of the keywords: mass customization, measures, metric, capability assessment, performance, performance assessment, and performance management. In addition to title and topic search, forward and backward search methods have been utilized. In total, 159 contributions have been found, which have been narrowed down to 21 papers by assessing against the following criteria: (1) giving recommendation for methods or approaches at performance assessment; (2) encompassing performance assessment by quantitative performance measures or assessment of organizational capabilities; and (3) addressing MC-specific challenges.

3.1 Performance Measurement Methodologies

The majority of the literature on performance assessment and MC applies a performance measurement perspective. From the literature review, 17 contributions and 11 methods have been identified, which are reviewed in the following:

- Blecker and Abdelkafi [2]: The purpose of the proposed method is to support companies in achieving a higher component commonality, thereby making MC work more efficiently. The proposed method enables evaluation of the overall commonality of a product family by using the total commonality index (TCI), which is an expression of the extent to which the variations of a product family can be produced around the same components. The metric indicates how well the company performs in relation to the product family design and the variety-induced complexity on the shop floor. No indications are given, however, of the appropriate level of TCI, though the authors suggest that benchmarking the index with the best in the industry could contribute in highlighting potential opportunities for improving product designs/redesigns.

- Blecker et al. [3]: In order to ensure well-founded variety creation decisions in MC, Blecker et al. introduce a key metric system for variety steering. The purpose of this method is to assess how well the company performs in gearing the product variety toward customers' real needs and managing the internal complexity level. The system, which is one of the most comprehensive of its kind, encompasses 32 key metrics, or KPIs, in total, which all indicate whether certain capabilities have been implemented.
- Bonev and Hvam [4]: The purpose of the proposed evaluation method is to initially give an assessment of the performance of ETO companies moving toward MC. The method builds on performance measurement of financial measures combined with a qualitative analysis of operational performance. The method introduces a procedural framework outlining four phases. It is conceptually described and addresses performance at a high level; the output of the measurement is thus only determined through additional qualitative analysis relying on subjective interpretation related to which capabilities need to be focused on in order to improve performance.
- Cormier et al. [7]: Cormier's proposed method aims at assessing the flexibility of a design in the early stages of the design process to ensure a sound product family design. The method proposes a set of metrics that uses early design information to evaluate the flexibility of proposed product architectures in the early stages of the design process. The method primarily gives recommendations about which metrics to utilize and measures only product-related aspects.
- Daaboul et al. [8, 9]: The purpose of the extended value network method is to evaluate MC strategies by supporting companies in the decision of whether to implement MC or not, and how better to implement it. The purpose of the method is more precisely to support in decisions regarding product and process variety, taking into account the impact on the perceived value for the customer. The method works as a decision-aiding system, allowing comparison of different alternatives for decisions on product and process variety. The method builds on a performance measurement system that assigns value based on 17 performance parameters and 6 main performance indicators, which are introduced in a framework together with a procedure for implementation and simulation.
- Fogliatto et al. [10]: The purpose of the method proposed by Fogliatto is to indicate MC feasibility and point at areas of the operations that require major improvements in flexibility to deliver products satisfying customer requirements; this is achieved by identifying gaps between customer demand and product and process performance. The measurement is implemented through the application of the Quality Function Deployment matrix. Recommendations are given mainly on how to compute the measurement, as the method is described at a rather conceptual level. The method thus does not offer guidance in what metrics to utilize, how to capture and describe customer requirements, etc. Furthermore, a way to translate the results so that areas for improvement are indicated is not described.

- Gero and Sosa [12]: The method proposed by Gero involves supporting the design process in generating a higher variety of solutions by assessing the complexity of the design space through complexity measures. The focus of this measurement is solely on the product aiming to maximize the solution space offered; the method does not take customer demand or process impact, performance or capabilities into consideration. Furthermore, the method is only applicable to MC strategies aiming at generating novel solutions, i.e., ones that use parametric or algorithmic solutions to yield a high degree of customization.
- Jiao and Tseng [13]: The purpose of the method proposed by Jiao and Tseng [13] is to measure the customizability of design, i.e., the cost-effectiveness of a design to be customized in order to meet individual customer needs. The aim is to maximize customer-perceived value by exploiting the potential of design to be customized. The performance assessment is mainly done through individual metrics, which is also the main focus of the recommendations given; some instruction is also given regarding how to conduct the customizability analysis; recommendations are given, however, at a rather conceptual level.
- Jiao and Tseng [14]: The purpose of this proposed method is to support companies in product family decisions, taking internal complexity and external variety into consideration. Jiao proposes two commonality measurements, a component part and a process commonality index, that can support companies in understanding and evaluating the product family. The proposed metrics can support the analysis of whether or not a product family is adequately designed. However, the method does not offer translation of the output of the measurement, nor indications of expected level, e.g., being ready for MC.
- Kumar [18]: Similar to the method proposed by Blecker et al. [3], the purpose of the method proposed by Kumar [18] is to support companies in variety decisions to help them find the optimal combination of MC and mass production strategies. Kumar [18] introduces a number of new metrics that measure the “mass” as well as the “customization” aspects of this strategy. The metrics focus on aspects such as modularity, customization degree, and level of exploitation of economy of scale. Recommendations are mainly given about which metrics to use, not the relations between them or how to deploy them to improve solution space capabilities.
- Nielsen and Brunoe [22]: The purpose of this proposed method, which is based on work in four earlier contributions [5, 23–25], is to provide information on a company’s performance as a mass customizer in order to focus the improvement effort; this is done by assessing the three fundamental MC capabilities. A number of metrics are introduced relating to each of the three capabilities, and two and six additional metrics are proposed for solution space assessment and process robustness, respectively. The three fundamental capabilities are assessed indirectly by linking the predefined metrics to the capabilities through a relationship matrix.

Based on the review of the contributions above, utilizing a performance measurement perspective in the MC performance assessment, it is revealed that the methods proposed by Blecker and Abdelkafi [2], Cormier et al. [7], Gero and Sosa [12], Jiao and Tseng [13], Jiao and Tseng [14], Kumar [18], and thus the great majority focus solely on supporting decisions regarding solution space development. A sound product family design is also pivotal for the success of MC, and having metrics supporting decisions about the product family is thus crucial. However, as the focus of these methods is only on assessing the attributes of the product with the aim of developing solution space capabilities, process performance and capabilities are, in most cases, not taken into consideration. If attention is given to process capabilities, it is only in trade-off decisions, assessing the impact of design decisions on process performance. These methods are due to the narrow focus, believed to offer limited guidance in the transition toward MC.

Another shortcoming of many of the proposed methods, such as [4, 7, 10, 12, and 13], is that the methods are only conceptually described and need further development before they can be implemented in industry to give mass customizers guidance in their transition toward MC.

For all of the methods utilizing a performance measurement perspective, a further shortcoming is that the methods in focusing at performance measurement do not make sure to translate or relate the results to organizational challenges. Only the methods proposed by Daaboul et al. [8], Nielsen and Brunoe [22] attempt to some extent doing this. Consequently, in order for the methods reviewed to be able to support the transition toward MC with adequate guidance, these methods need to be further developed, so that the methods more consistently and thoroughly point out areas and capabilities for improvement.

3.2 Capability Assessment Methodologies

Only three out of the 21 contributions give methods for assessing capabilities, not including the methods with a combined focus, which are reviewed in the following section.

- Berman [1]: The purpose of the assessment method introduced by Berman [1] is to assess a company's readiness to adopt an MC strategy. The method builds on a capability assessment made by using a vertical audit against 21 checkpoints. The method only gives recommendations about which assessment points should be utilized, and no guidance is given on the relationship between measurements or the translation of the results.
- Tu et al. [30]: The proposed method is to measure the level of modularity-based manufacturing practices and their impact on MC capability. The method aims at ensuring that the necessary organizational capabilities within manufacturing leading to customization are implemented. The capability assessment method gives recommendations for 15 items or capabilities to be used as individual measurements, and a framework connecting the capabilities is introduced. Having knowledge about the capabilities of manufacturing practices and their

impact on MC capability is definitely valuable in the transition toward MC. Modularity-based practices are one of the primary means of achieving MC capability.

- Pishdad and Taghiyareh [27]: The purpose of this proposed method is to support management with information on organizational readiness for MC by letting managers utilize their knowledge and understanding of the firm to develop a profile of the company before committing to an MC plan. The methods build on capability assessment and introduce a capability framework consisting of 26 capabilities or factors that are used in assessment by appointing scores from either a 3-, 5-, or 8-point scale. However, no guidance is given regarding how to assess the performance of each of the factors, no goals or benchmark items are introduced, and the assignment of scores is thus based on subjective input, which reduces the reliability of the result. In addition, the relationship between the measurements is not described.

A shortcoming to highlight that is common in each of the three methods is that the performance assessment alone builds on either management's subjective input or acquiring input from the organization. Performance is not quantified, e.g., by performance measures giving operational or financial figures, which makes the performance of MC harder to quantify. Another shortcoming of the proposed method by Tu et al. [30], in relation to giving feedback in the transition toward MC, is that the method, by focusing on the manufacturing processes, is limited in scope, as assessment is done only on the three fundamental capabilities.

A third shortcoming of the proposed methods is that the methods proposed by Pishdad and Taghiyareh [27] and Berman [1] only offer guidance to companies that are in the consideration or planning stages of implementing an MC strategy. This makes the proposed method based on this lack valuable information in the transition toward MC.

3.3 Combined Assessment Methodologies

In contrast to the great majority of contributions on performance assessment within MC, the following two methods apply a more holistic view of performance assessment, taking both performance measurement and capability assessment into perspective.

- Kumar and Stecke [17]: The performance assessment method introduced by Kumar [18] aims to determine the effectiveness of a firm's MC strategy, i.e., the extent to which a company's MC and personalization strategy has been effective in enhancing a company's strategic advantage. This method relies on performance measurement and capability assessment combined in a computational index called an MC and personalization effectiveness index (MCPEI). Recommendations are given at the individual, structural, procedural, and systemic levels. The method gives recommendations for three compound measurements or components of the MCPEI: a market-based measurement that gives the market's perception of effectiveness, a capability-based measurement based on the company's capabilities, and a combined measurement of the two components.

- Storbjerg et al. [29]: The purpose of the method proposed by Storbjerg and Nielsen is to support companies that are aiming to implement or improve their choice navigation capabilities, with performance assessment supporting the change process. Building on theory and a model from continuous improvement theory, the method combines measurement of performance with capability assessment. These two forms of measurement are introduced as constructs in a framework and as related to the success of MC. Besides the framework, the method only gives recommendations for general performance assessment methodologies.

The method proposed by Kumar and Stecke [17] enables a company to assess the effectiveness of its strategy. Furthermore, the index enables benchmarking with other companies to give input on best practice, and the method is based on this, considered to be relevant in giving valuable information in the transition toward MC. However, two drawbacks can be identified from the suggested approach. First, the capability assessment is based on a limited set of capabilities, making the assessment narrow in scope. Second, the suggested approach for assessing the capabilities is a subjective evaluation by the management team, which gives the data needed for calculating the index by assigning a score from 1 to 10. This significantly reduces the reliability of the result of the measurement and reduces its usability for benchmarking.

On a conceptual level, the method proposed by Storbjerg et al. [29] is also considered relevant for providing information for the transition toward MC. However, recommendations at a conceptual level are not sufficient, and the method is thus not considered adequate in present form for giving feedback to companies in their transition toward MC. Another shortcoming of the method is that it focuses only on one of the fundamental capabilities, choice navigation, which makes it narrow in scope.

In summary, 21 contributions have been reviewed, from which 16 performance assessment methods have been analyzed. Based on the analysis, five shortcomings, common to some or several of the methods, have been identified. The methods are as follows:

1. Narrow in scope, not supporting the full set of capabilities highlighted in the literature as necessary for a successful transition to MC.
2. Narrow in purpose, only supporting the decision about adopting an MC strategy, not the deployment of the strategy.
3. Not operational or possible to implement, as the methods are only conceptually described and do not give recommendations at all levels, i.e., individual, framework, and system levels.
4. Product focused, only offering support for decisions about variety steering.

5. Unilateral in assessment, either metric focused or capability focused. No translation of performance results in capabilities and capability areas that need to be improved, and vice versa.

Based on the shortcomings identified through the analysis, none of the available methods have been assessed as fully capable of giving feedback information to the change process toward MC. The results of the analysis are summarized in Table 1, which also includes the five general shortcomings identified.

4 Discussion

Based on the results of the analysis, an obvious question for discussion is whether the aim should be to develop one method capable of supporting the wide-ranging and complex needs of supporting the change process of implementing a MC strategy. One dimension within this line of discussion is whether there, at all, is a need for having a method both giving input on MC performance in quantitative terms by performance measurements, e.g., financial measures, and in qualitative terms by capability assessments. The two approaches each have their benefits; performance measurement enables, if properly designed, clear indications of the output performance of processes, which leaves out discussions of, in this case, the success of the MC strategy. However, performance measures do not work effectively in pointing out the causes for the performance level. At best, areas or functions contributing positively or negatively to the performance level are indicated. This leaves management unanswered on what to do in order to improve performance. Furthermore, many of the performance measurement methods tend to express the output performance and thus work as lag indicators. In contrast, capability assessment enables early indications of the output performance and can as such work as lead indicators. In addition to this, some capability assessment methodologies, as highlighted in [20], [29], enable not only assessment of performance, i.e., capability or maturity level, but also give guidance in which activities should be put in place to achieve a higher performance level. We argue based on this that MC performance assessment, given the fundamental nature of performance measurement and capability assessment, respectively, needs to address both elements in order to give adequate guidance in the change process of implementing MC.

Another dimension to discuss in relation to the prior question is whether it is practical or even necessary to have one method covering the broad nature of MC capabilities. Building on that, in order to become a successful mass customizer, a company needs to develop all three capabilities; we argue based on this that a comprehensive performance assessment method is needed.

Another relevant dimension to discuss in relation to the initial question is how big a drawback having performance assessment methods that do not give recommendations for how to conduct assessment on all the levels earlier discussed is,

Table 1 Analysis of 16 MC performance assessment methodologies. SSD refers to solution space development, CN to choice navigation, and RPD to robust process design

	Capability	Performance	Combined	Individual	Procedural	Structural	System	SSD	CN	RPD	Legend x Fit (x) Partial fit				
	Type of performance assessment			Level or type of recommendations				Relevance to the MC capabilities			Shortcomings				
											1	2	3	4	5
Berman [1]	x			x				x	x	x		x	x		x
Blecker and Abdelkafi [2]		x		x				x			x			x	x
Blecker et al. [3]		x		x	x	x	(x)	x	x	x					x
Bonev and Hvam [4]		x		x	x			(x)	(x)	(x)		(x)	x		x
Cormier et al. [7]		x		x				x			x		x	x	x
Daaboul et al. [8, 9]		x		x	x	x	(x)	x	(x)	(x)	(x)			x	(x)
Fogliatto et al. [11]		x		x	x		(x)	x		x	x		(x)	(x)	x
Gero and Sosa [13]		x		x				x			x		x	x	x
Jiao and Ts eng [14]		x		x	x		x	x			x		x	x	x
Jiao and Tseng [15]		x		x				x			x		x	x	x
Kumar and Stecke [18]	x	x	x	x				x	(x)	x	x		(x)		
Kumar [19]		x		x				x			x		(x)	x	x
Nielsen and Brunoe [23]		x		x		x		x	x	x			(x)		(x)
Pishdad and Taghiyareh [27]	x			x		(x)		x		x	x	x	x		x
Storbjerg et al. [30]	x	x	x			x			x		x		x		
Tu et al. [31]	x			x	x	(x)				x	x		x	x	x

e.g., methods that only give guidance on a metric level. Having a method giving only the metrics to be utilized leaves the user with a larger implementation and interpretation task. Similarly, having a method that only gives recommendations at a framework level leaves the user with a huge task in developing the method, e.g., clarifying relevant measurements or checkpoints. We thus argue that a method needs to give recommendations at all levels in order to give proper guidance.

Finally, it is worth discussing whether it is relevant, considering the broadness of the available MC strategies, to develop a generic MC performance assessment methodology. This discussion has been initiated by Blecker and Abdelkafi [2], who, based on the fact that there is not only one way to achieve MC, highlight the challenge of setting up a general assessment method. One way of dealing with this challenge is to build certain flexibility into the performance assessment methods, such as by suggesting different metrics, capabilities, and capability areas for the different levels of customization proposed by Daaboul et al. [9].

5 Conclusion

In this paper, we give an overview of the literature addressing performance assessment within MC. Focus, level of recommendation, and relevance of the available methods for the fundamental capabilities of MC are evaluated. Based on this, the ability of the methods to give relevant feedback information in the organizational change process of implementing MC is evaluated.

Based on an extensive search of the literature within MC addressing performance assessment, more than 150 contributions have been identified. By reviewing the general literature on performance assessment, relevant points for classification and evaluation have been identified, and a framework for review has been developed.

By a thorough review of 21 contributions, it is concluded that the dominating perspective in the literature on performance assessment is a performance measurement perspective; only 5 out of 21 contributions address how to assess capabilities. It is furthermore concluded that the great majority only covers one dimension; only two contributions attempt to bridge the assessment of performance and capabilities

With 16 out of 21 contributions on topics related to variety steering, the majority of methods attempt to support development of solution space capabilities. In contrast, only six methods attempt to address assessment of the choice navigation capabilities.

Furthermore, it can be concluded based on the analysis that only a limited number of the available methods aim at assessing performance more broadly, covering all the fundamental capabilities.

Based on the analysis, five more general shortcomings, common to some or several of the methods, have been identified. Based on the shortcomings identified, none of the available methods have been assessed as fully capable of giving feedback information to the change process of MC.

None of the proposed methods have treated the task of proposing a framework as a design task, clarifying requirements, proposing different solutions for the requirements, selecting the best-fitting solution, and testing the method. We see this as a clear avenue of future research; a sound start would be to clarify general requirements for performance assessment from both change management literature and potential users in industry. From this starting point, a further potential area for future research is to develop a more holistic performance assessment system building on both measurement of performance and capability assessment.

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Mass Customization as Innovation Driver of International Competitiveness in Peripheral Regional SME Subcontractors

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Abstract The manufacturing literature has for long been occupied with the linking of manufacturing capabilities with the competitive advantages of the company. The dominant manufacturing content approach is concerned with the consistent set of decisions about process technology design and organizational practices that can be exploited as competitive capabilities. This paper suggests that an open network structure demands a transformation of peripheral-located SME subcontractor from traditional customized producer to mass customized producer. Mass customization as an instrument for the transformation process consisting of practical tools on many different company levels will comply with the challenges the international competition charts.

Keywords Organizational · SME · Mass customization · Modularity · Regional development

1 Introduction

In significant hostile competitive environments forced by dramatic changes in technological and economic global infrastructures, companies are seeking new competitive edges.

The rapidly evolving nature of establishing international manufacturing operations reflects the changing dynamics on how companies gain and sustain competitive advantage. The manufacturing company strives to acquire new competences from deployment of resources and renewal of company capabilities that change the competitive environment in its favor.

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The driver in the changing process is the dominant economic price paradigm where efficiency in all parts of manufacturing operation is believed to obtain cost advantages as core competence for sustainable competitiveness.

The increasing global hostile battlefield on cost advantages has recently been enlarged by incumbent companies desperately seeking profit opportunities by moving their cost curve from established market to developing markets such as China, India, and similar. The consequences for small and medium enterprise (SME)-sized manufacturing companies located in peripheral region might be dramatic.

The larger manufacturing companies steadily seek location advantages outside peripheral regions leaving the SME without their traditional supply chain livelihood. The traditional competitive advantage of subcontractors based on efficiency and control runs out of advantages.

Their customers constantly redesign their supply chain from a closed integrated whole to an open international network structure leaving the subcontractors in a global battlefield of creativity, flexibility, and timing. Because integration will tend to exclude integrated units from interaction with the broader set of potential users, producers accommodate companies that are seeking new organizational forms in loose-coupled networks without trammels. In the integrated supply chain, the competitive advantage as a whole is critical. In an open network structure, every single part of the supply chain is challenged by competitors with the same focus on each productive element [1]. Dynamic capabilities [15] are demanding by the modern manufacturing company which by itself can be viewed as a dynamic community, focusing on the modularity of companies' resources, the processes by which these resources are dynamically reconfigured as markets and company players coevolved [5].

In an open and flexible knowledge, network competitive advantages are not any longer bound to traditional parameters as efficiency, control, and cost. Such parameters are qualifiers [7] in the international competition, whereas learning to construct innovation capabilities becomes the future order winners.

This paper argues that in peripheral regions, the challenge for SME subcontractor is the transformation from traditional efficiency supplier to open innovation agency. This transformation process has several dimensions. One important is the solution space the product portfolio encompasses. Enabled by technologies such as computerization, internet, product modularity, process flexibility, the solution space of the subcontractors' product offering accommodates the challenges in an open network structure.

We have organized the paper in three sections. The first section is concerned by the structural characteristic dominating a Danish peripheral region. The next is a theoretical outline of mass customization as framework for transforming the traditional SME subcontractor culture to an open innovation network culture. The final section is recommendation to a road map of the transformation process.

Fig. 1 Regions in the Kingdom of Denmark, in the *top* (*yellow*) Northern Region

Table 1 Total number of companies, employees, turnover, and export, and selected line of business [1]

	Companies	Employees	Turnover mill, EURO	Export mill, EURO
Total	31,739	178,476	30,180	7,790
Agriculture	6,277	5,092	2,538	82
Industries	2,738	26,706	8,187	3,451
Construction	3,327	12,704	2,407	79

Source (Statistikbanken 2013)

1.1 Northern Jutland: Structural Characteristic

Northern Jutland is part of the mainland of the Kingdom of Denmark (Fig. 1) with a population of 0.6 million and with an occupational structure dominated by SME companies.

The largest geographical area is an island, separated from the mainland by the Limfjord. Selected figures in Table 1 make a short statistical structure of the region. The line of business in Table 1 is characterized by production. Approximately 70 % of all industrial companies employ less than 100 employees. Between 2005 and 2010, companies with more than five employees generated a growth in turnover with more than 10 % [11]. They found that companies exist within all sizes and identified special strength characteristics to growth:

- Low level of hierarchy and informal tone with strong crosswise team work.

Table 2 Industrial SME in Northern Jutland and total amount of companies

SME	2010	2011
Micro-companies < 10	1,211	1,227
Small companies < 50	522	500
Middle companies < 100	158	169
Total SME	1,891	1,896
Total industrial companies	2,738	
Total SME (%)	69	

Source (Statistikbanken 2013)

- Steady and engaged employees with high degree of responsibilities and planning capacity and skills to solve unexpected problems.
- Market understanding with a high level of navigation capacities in uncertain surroundings.

Of challenges, the research found capital scarcity and management resources and skills to develop new industrial business models together with limit resources of qualified employees [11].

Companies located to Northern Jutland have an inward focus in their sales activities, and only export approximately 25 % of the production [4]. The region is the least-exporting region in Denmark, and for companies exporting, the main market is nearby the border of Denmark: Norway, Sweden, and Germany. Furthermore, it is documented that people settled in Northern Jutland believe that overall activities within society must be focused on internal local activities instead of global activities, and many people are seized with fear [18].

Region Northern Jutland has set six consecutive business clusters as priorities growth generator for employment and economic income (Table 2). The report recommends knowledge, knowledge sharing, and innovation to strategic instrument [4].

The business clusters employ more than half of the total employment in Northern Jutland. According to statistics Denmark [2], approximately 31,000 people are employed in the industrial sector in Northern Jutland. Even though there are widely different frames, customers, and size, a convergence of the strategic development of competences necessary to survival in a dynamic and changing global competition has common characteristics. These are the coherence between future line of business, strategies, competitive resources, and skills.

The criterion for the cluster is a complex concept focusing on integration of personal and professional skills as growth generator in the region.

Region Northern Jutland is part of the "Big H," which is the overall government infrastructure investment plan for urban development, income growth, and logistics (see Fig. 2). The geographical location of Denmark demands an infrastructure which links the country to the rest of Europe, especially to the nearest surrounding countries, because these countries are the most important trading partners. Seventy percentage of the Danish export is traded within the European Union (Table 3).

Fig. 2 The Danish infrastructure investment plan 2030 (the “big H”)

Table 3 Employees in six strategic development cluster, Northern Jutland, 2006

Business	Employees	Pct	Avg. in DK
Food	35,921	13	9
Construction	41,872	15	13
ICT	8,990	3	4
Health	34,945	13	13
Industry	5,207	2	1
Leisure economic	14,020	5	6
Cluster total	141,015	51	47

Source (Fremkom 2012)

Placed at the northern end of the European continent and the outskirts of the Big H and with an introvert perspective, the region faces a big challenge to generate economic growth and new manufacturing jobs. It is very difficult to put forward suggestions for growth in the future [4].

An interesting point is that future growth potentials are placed in the intersection between traditional industries and divided technologies and knowledge domains. We also argue that changes are pressing for the SME understanding of traditional business model and product offering. Growing unpredictability to customer demand of product specifications and accelerating technology development of production systems require development of reconfigurable and scalable manufacturing processes which can accommodate dynamic and changing demand of individualized products.

2 Modular Organizational Forms

Dramatic changes in the nature of many companies take place in the transition to a global society. The locus of production is no longer within the boundaries of a single company, but occurs instead at the nexus of relationship between varieties of parties that contribute to the production function [13]. To be flexible, companies need to be recombined into a variety of configurations much as a modular product system which enables multiple end-product configurations from a given set of components, but heterogeneity in resources leads to differentiated capabilities and to put them at a competitive advantage is limited by the structural characteristics of SME. Companies are encouraged to specialize in those activities in which their rate of return is highest. Further, the more heterogeneous the demands made upon a company, the pressure to produce more alternative configurations from the same inputs available will be commanding and the more valuable the flexibility becomes.

We argue that region Northern Jutland need to support what we term dynamic community [5] by the following features: SME structure that displays modularity (generating resource and process diversity among companies with specialties and display product systems offering as new productive assets in the context of changing markets). Supporting modular organization forms is an innovative feature to growth generation.

3 Characteristics of Mass Customization and Modularity

Mass customization has long been known as a competitive strategy for delivering individually customized products at costs near mass production, bringing inexpensively tailored products to the end customer [10]. Applying MC implies a number of benefits to companies: the ability to charge a price premium [9, 10] and economies of integration giving access to market information and customer loyalty [9]. Prominent examples of MC includes customized computers from Dell, which are all configured to individual customers' requirements; custom shoes from Adidas or Nike; as well as the car industry where MC is widely adopted allowing customers to configure hundreds of different options within a specific car model.

In the competition against manufacturing in low-wage countries, shifting to a mass customization strategy is a major possibility for Danish manufacturing companies, since flexibility, innovation, and responsiveness are all proven strengths of Danish industry as opposed to low-cost manufacturing. Furthermore, due to logistics of individually customized products, Denmark will have a competitive advantage due to closeness to the European markets and experience within manufacturing of small series. Hence, shifting the focus to MC would be an enabler for growth in the Danish industry and increasing the employment of Danish workforce.

It is commonly acknowledged that the usage of modular product architecture is an efficient way of creating the product variety necessary in mass customization [3, 16, 17]. Furthermore, the usage of modular product design has proven to have a number of long-term positive effects on product development as well as manufacturing and logistics [5]. Numerous definitions of modular product architecture exist, but in this context, the definition of modular product architecture defined by Ulrich and Eppinger [17] is adopted. This definition states that products with modular architectures have the following properties: (1) One module, being a part of the product, implements one or few functional elements and (2) the interactions and thereby interfaces between modules are well defined [17]. This applies to physical products and may to some extent also apply to digital products. However, digital products' variety can also be implemented without the usage of a physical modular architecture, since products can be customized by nonphysical means. Ulrich and Eppinger [17] define three different types of modularity: (1) slot modular architecture, (2) bus modular architecture, and (3) sectional modular architecture. In the sectional modular architecture, however, all interfaces between modules are identical, implying that modules can be combined randomly, and no module is common to all products in a product family.

Modular product architecture broadly defined is often considered the opposite of integral product architecture, in which products are not logically divided in modules with clear interfaces. This architecture is typically chosen for performance reasons, when size is an important optimization issue or if the product is produced in a volume, where the accumulated variable costs exceed the savings from choosing modular architecture.

A variation in the modular product architecture is the platform architecture. The concept of a product platform has been defined by numerous scholars. McGrath [8] defines a product platform as: "a collection of the common elements, especially the underlying core technology, implemented across a range of products." This definition is embraced in this context since it defines very well the characteristics of a product platform related to the product itself, where other definitions also focus on processes, knowledge, and organization [12]. The usage of product platforms has proven to be a very efficient way of creating a product family with a high variety at a low cost. This is done by implementing the common functions of a product family in a platform and implementing the differentiating characteristics in modules which are combined with the platform. Simpson [14] defines two types of platform-based product families; the module-based platform family and the scale-based platform family. The module-based product family is customized by adding or removing modules from the platform, whereas the scale-based platform is customized by stretching or shrinking the product design. However, there are also known examples of product families which embed both principles in the customization process. The platform product architecture is a subtype of the modular product architecture, which implies that a platform-based product is also modular; however, a modular product is not necessarily platform based. As mentioned above, Ulrich and Eppinger [17] defined two modular architectures which can arguably be characterized as platform architectures. The slot modular architecture is defined by a common module or set of modules with a number of slots in which certain module types will fit. Each slot, however, only fits one module type, and modules can thus not be interchanged. The modules which fit in the slots are thus used for differentiating the individual products, and the common modules can be considered the product platform. The bus modular architecture also defined by Ulrich and Eppinger [17] is similar to the slot modular architecture; however, modules are interchangeable. In the platform architecture, a number of common modules will constitute the product platform containing the “bus,” whereas the differentiating modules used for customizing the product are fitted onto the bus. This implies somewhat greater flexibility compared with the slot modular architecture; however, the requirements for a common interface may render this architecture impractical in some applications.

Hence, if Danish manufacturers are to exploit the opportunities in mass customization, they must master the disciplines of modularity and product platforms. Though theory provides extensive knowledge on the topic, many companies have faced significant challenges implementing this product architecture [6]. On the other hand, mass customization provides great opportunities for competing on different parameters than low manufacturing costs, and since it requires high process robustness, it is considered ideal for a region like Northern Jutland. We argue above that Northern Jutland must also aim at establishing itself as a “dynamic community” and utilize modular organization forms in order to produce high-quality products by combining the competencies of different companies to meet specific varying requirements. However, in order to do this, product modularity is key, since the definition of clear interfaces between different modules will be critical in the integration of subparts or modules of products needed to produce a whole product.

4 Conclusion

Peripheral regions in Denmark, as well as in similar countries, face a number of different challenges, one of them being the transition from traditional efficiency supplier to open innovation agency. This transformation process has several dimensions. One important is the solution space the product portfolio encompasses. Enabled by technologies such as computerization, internet, product modularity, process flexibility, the solution space of the subcontractors’ product offering accommodates the challenges in an open network structure.

We argue that region Northern Jutland needs to support the concept dynamic community by the following features: SME structure that displays modularity (generating resource and process diversity among companies with specialties and display product systems offering as new productive assets in the context of changing markets). Supporting modular organizations forms is an innovative feature to growth generation. Furthermore, the business strategy mass customization provides important opportunities to provide competitive product offerings for the market as well as close export markets, which are traditionally important for Northern Jutland. However, to support modular organization forms, product modularity must be implemented in the individual companies to enable integration. Furthermore, increasing the modularity in organizations as well as products will enable companies in Northern Jutland to enter new markets for mass customization.

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Mass Customization Measurements Metrics

Kjeld Nielsen, Thomas D. Brunoe, Kaj A. Joergensen and Stig B. Taps

Abstract A recent survey has indicated that 17 % of companies have ceased mass customizing less than 1 year after initiating the effort. This paper presents measurement for a company's mass customization performance, utilizing metrics within the three fundamental capabilities: robust process design, choice navigation, and solution space development. A mass customizer when assessing performance with these metrics can identify within which areas improvement would increase competitiveness the most and enable more efficient transition to mass customization.

Keywords Mass customization · Metrics · Measurement · Capabilities

1 Introduction

To address the increasing customer demand for individually customized products, mass customization has been widely adopted as a competitive business strategy during the last two decades [1, 2, 3, 4]. Up to 17 % of companies have within the first year experienced that the implementation of mass customization is much more complicated than immediately anticipated and in some cases even jeopardized the existence of the company instead of increasing competitiveness [5]. Meanwhile, others such as Dell, BMW, and Adidas have shown that success is indeed feasible [4].

The reason why shifting to mass customization is so difficult is that it is fundamentally different from mass production. In product development, families of

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products must be developed instead of individual products. In the sales process, vast amounts of information must be exchanged between customer and company to configure the right product and allow the company to manufacture it. In manufacturing, products are manufactured in batches of one as opposed to mass production where batches are hundreds or thousands of identical products. This basically renders a mass production system ineffective in relation to mass customization manufacturing. In relation to logistics, a specific product must be distributed from the manufacturing facility to the end customer, whereas in mass production, a number of products are shipped from the manufacturer to a warehouse to a retailer where it is sold to the end customer. This further introduces a challenge since mass customization products cannot be stocked and can only be produced once a customer order is given. All the challenges described above need to be addressed if a company wishes to pursue a mass customization strategy, which in many cases has proven more difficult than anticipated.

1.1 Mass Customization Capabilities

Recent research has shown that the ability to transform a business into a successful mass customization business depends primarily on three fundamental capabilities [5, 4]: (1) "Robust Process Design—Reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs," (2) "Solution Space Development—Identifying the attributes along which customer needs diverge," and (3) "Choice Navigation—Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice." A company mastering each of the three capabilities will thus have increased chances of succeeding as a mass customizer [4]. Although these three capabilities are identified and described theoretically in literature, mass customization companies are still faced with a challenge when evaluating their capabilities to identify where performance lacks since no integrated method is available serving this purpose.

The objective of this research is to identify the relations between mass customization capabilities, the sales and operations in a company and ultimately the profitability and thereby competitiveness of the company. Furthermore, the aim is, by identifying these relations, to be able to measure a company's performance within each capability and thereby indicating which tools and methods should be applied with the greatest improvement as a result.

1.2 Mass Customization Performance Measurement

Performance measurement has long been applied as a tool for improving performance, and since tools like the balanced scorecard have emerged, focus within performance measurement has to some extent shifted from purely financial measures to now also include non-financial measures [6]. Many publications indicate that performance measurement does in fact improve performance; the evidence has been much discussed in literature [7]. It has proven a tremendously useful tool for assisting in improving performance, performance measurement itself cannot guarantee performance improvement, since the effect of performance measurement depends on a number of factors [7]. Bourne et al. [7] analyzed these factors and organized them into three groups: (1) context (2) content, and 3) process. The context factors include the companies' external environment as well as internal factors such as structure, culture, strategy, and resources [7]. The content factors are related what the performance measurement system actually measures, i.e., the definition of measures, dimensions, and structure of the measures [7]. Finally, the factors related to the process address the process in which the measures are (1) designed, (2) implemented, (3) used, and (4) refreshed.

Hence, a high number of different factors determine whether a performance measurement system has a positive effect on performance, both factors which can be influenced during the development of a performance management system, but also the contextual factors.

Relating this to a mass customization context, a performance measurement system for mass customization should be designed with these different factors in mind, but it also implies that one single performance measurement system will not fit all mass customization companies, since these companies will have different contexts. However, literature generally agrees that performance measurement systems should be aligned with the companies' strategies [6].

In order to develop the three fundamental mass customization capabilities described by Salvador et al. [4], performance measurement is considered an important enabler, however, the performance measurement system must be developed specifically to fit mass customization and for a specific mass customization company to be effective. In this research, we look into the specific content, rather than context and process of performance management systems to address the three fundamental capabilities.

In the research presented in this paper, we identify the metrics needed to develop a performance measurement system for mass customization, assuming this will be a valuable tool for companies to be able to establish themselves as mass customizers or for existing mass customizers to improve performance. The research question is:

What metrics can be used to measure performance and thereby assess capabilities for choice navigation, solution space development, and robust process design and how can these be determined?

The research question has been answered through first defining each capability, and in overall terms, what should be assessed. Then, a literature review is conducted to identify related metrics already defined in literature. These metrics are evaluated, whether they are descriptive in relation to the three capabilities, and a final set of metrics is developed for each capability. In previous papers, thorough literature reviews have been conducted and metrics defined in greater detail [3, 8, 13, 9].

2 Metrics

Three fundamental capabilities in mass customization have been analyzed for key performance indicators during literature reviews and explorative research. To support this work, each capability has been analyzed to establish evaluation criteria sets for each of the three capabilities. Because of the different nature of the capabilities, no common evaluation criteria set has been established. The evaluation criteria sets have been chosen on individual basis for each of the three capabilities, with two goals in mind (1) they must be measurable; otherwise, they are per definition not metrics and (2) the required data should preferably be readily available in the company or should be easily obtainable. Luckily, most mass customization companies have information systems which could support this, such as configurators, product lifecycle management (PLM) systems, enterprise resource planning (ERP) systems, engineering change management (ECM) systems, which are expected to provide most of the required data.

The authors have in previous research made a comprehensive presentation of potential metrics for each of the three capabilities and based on the evaluation criteria made a selection of metrics [3, 8, 13, 9]. Each metric's value has accordingly been verified for valuable information about the capability. These selected and verified metrics are presented as a walk-through of the metrics one by one, with name, equation (if existing) and a verification of how the metric's value can assist assessment and measurement in the specific capability.

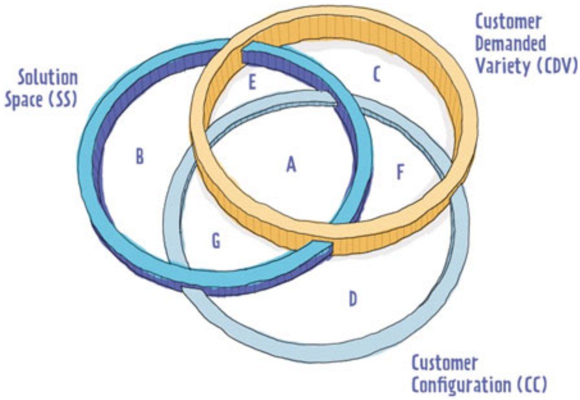
2.1 Choice Navigation Metrics

The choice navigation capability is related primarily to the capabilities of the configuration system, and its ability to configure a variety of products. The customer experience from a product configuration process should aim for a result where the customers recognize that the configuration process supports the customer's requirements and offers the products which fulfill the customer's exact needs [4].

Supporting the customer in the process, making the product configuration easy and fast, is a matter of making it easy to match characteristics of needs, empower customer in building models of needs, or embed the configuration in the product [4], from an assessment point-of-view this is potentially measurable. Measuring how well the choice navigation ensures a 100 % fit between customer needs and the goods configured by the customers, however, seems more difficult.

In choice navigation, the evaluation criteria set has been established with introduction of three sets and their intersections (see Fig. 1): solution space (SS), products and variants developed by the company, customers demanded variety (CDV), expressing customers' needs, and finally customers configuration (CC), an expression of the configuration actually done by the customer (or sales personal).

Fig. 1 Evaluation criteria's for choice navigation



Analyzing Fig. 1, intersections B and C are consequences of a mismatch between the actual demand and solution space, where B implies variety which is part of the solution space but has no demand thus potentially implying unnecessary complexity costs. C implies a demand for variety that is not met by the current solution space and which may indicate an intersection where the development of the solution space could increase sales. The D intersection is seemingly less interesting in terms of choice navigation, since they relate primarily to the capabilities within solution space development.

In intersection D, the customer configures a product that does not meet the demand nor is it contained in the solution space. This is not a typical situation, but is nevertheless undesirable and would likely be indicated by the customer abandoning the configuration. In intersection E, there is a match between the variety offered by the company and the customer demand; however, the customer does not configure the product. This is likely a result of a user interface unable to guide the customer satisfactory through the configuration process. Intersection F indicates configuration, which match a customer demand, but is outside the actual solution space, i.e., a product that can be configured but not produced, which is also highly undesirable. Finally, in intersection G, the customer configures a product that is within the solution space but does not meet the demand thus resulting in a customer disappointment.

Configuration abortion rate metric (CA) source: [10]

$$\mathrm{CA} = \frac{N_a}{N_p}$$

CA configuration abortion rate metric
N_a: number of aborted configuration processes
N_p: number of logins (started configurations)

The CA metric describes how frequently customers or sales people choose to abort a configuration which has been initiated due to whatever reason. A high CA value can be used as an indication, for intersection E (see Fig. 1), since customers that cannot configure a product to meet their requirements will likely abandon the configuration.

Customers return rate metric (RTR) source: [11]

$$\mathrm{RTR} = \frac{\text{number of returned products}}{\text{number of delivered products}}$$

The RTR metric describes how often customers return a product to the company after receiving it due to, e.g., disappointment in the product.

In this case, customers realize that the configured product does not meet requirements, after it is received. In this case, the customer may return the product, which then is indicated by RTR. High RTR value indicates information about intersection G, an area within solution space but no customers' need.

Customers churn rate metric (CR) source: [12]

$$\mathrm{CR}(\Delta T) = \frac{\mathrm{NOLC}(\Delta T)}{\mathrm{NOC}(\Delta T) + \mathrm{NONC}(\Delta T) - \mathrm{NOLC}(\Delta T)}$$

NOLC	number of lost customers at ΔT
NOC	number of customers at T
NONC	number of new customers at ΔT

The CR metric describes the relationship between new customers and lost customers. High value of CR indicates information about intersection G, an area with solution space but no customers' need.

Customers repurchase rate metric (RR) source: [11]

$$\mathrm{RR} = \frac{\text{repurchase through existing customers}(\Delta T)}{\text{number of new customers}(\Delta T)}$$

The RR metric describes how often products are repurchased, or how often customers return to purchase another different product. A low value of RR indicates information about intersection G, an area with solution space but no customers' need.

Customers complaints rate metric (COR) source: [10]

$$\mathrm{COR} = \frac{\text{number of complaints}(\Delta T)}{\text{numberof deliveries}(\Delta T)}$$

Similar to the CR metric, the COR metric describes how often customers complain over a product they have purchased after receiving it. A high value of COR indicates information about intersection G, an area with solution space but no customers' need.

Seller order cancellation rate (SOCR) source: [13]

$$\mathrm{SOCR} = \frac{\text{number of orders canceled by seller}}{\text{number of placed orders}}$$

The value of metric SOCR can have several reasons; one could be, customers configure products which are within the customer demanded variety but outside the solution space, i.e., a product is configured which cannot be delivered. This would likely result in the order being canceled by the company, since it cannot be manufactured. High values of SOCR would then indicate configurations within intersection F, an area with customers need but no solution space.

Seller order change rate after purchase (SOCRAP) source: [13]

$$\mathrm{SOCRAP} = \frac{\text{number of orders changed by seller}}{\text{number of placed orders}}$$

If a configuration is inside customer demand variety but outside solution space, an alternative to cancellation would be that the company will change the configuration to fit within the solution space by, e.g., upgrading the product. High values of SOCRAP would then indicate configurations within intersection F.

Customer order cancellation rate (COCR) source: [13]

$$\mathrm{COCR} = \frac{\text{number of orders canceled by customer}}{\text{number of placed orders}}$$

In this case, the customer configures a product, which is within solution space but does not correspond to the customer's requirements and if the customer realizes that the product is not satisfactory prior to delivery, the customer may cancel the order. High values of COCR could indicate configurations within intersection G, an area with solution space but no customers' need.

Customer order change rate after purchase (COCRAP) source: [13]

$$\mathrm{COCRAP} = \frac{\text{no. of orders changed by customer}}{\text{number of placed orders}}$$

In this case, the customer configures a product, which is within solution space but does not correspond to the customer's requirements and if the customer realizes that the product is not satisfactory prior to delivery, the customer may alternatively change the order. High values of COCRAP could indicate configurations within intersection G, an area with solution space but no customers' need.

Configuration sales rate metric (CSR) source: [13]

$$\text{CSR} = \frac{\text{number of sold configurations}}{\text{number of started configurations}}$$

CSR indicates, when values are high, that most configurations lead to a sale and hence an indicator of being on target with choice navigation. Since configurations within intersection A should lead to a sale, then an increase in CSR would also indicate an increase in configurations within intersection A, the area which satisfy the customer, with solutions space and potential configuration opportunity.

2.2 Solution Space Development Metrics

In order to establish metrics for solution space development and developing measurement techniques, it is important to have some sort of idea of what constitutes a "good" solution space or even an optimal solution space.

A set of performance parameters has been introduced as evaluation criteria's for metrics in solution space development, these parameters are presented in Fig. 2. Selected metrics for assessment and measurement of solution space development are as follows:

Aggregate solution space profitability (ASSP) source: [14]

$$\text{ASSP} = \text{Total Sales income} - \text{Total manufacturing cost}$$

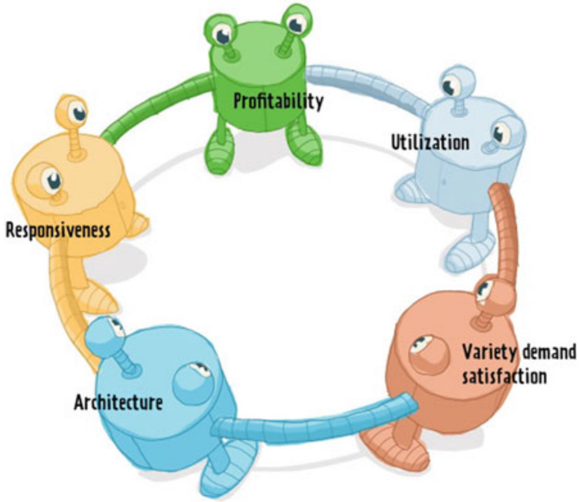
The metric ASSP is a measure of how profitable the solution space is as a whole and should be measured over a period of time.

Profitability per product family (PFP) source: [14]

$$\text{PFP} = \text{Sales income from product fam} - \text{manufacturing cost for product fam}$$

This metrics requires high data availability and detailed data about manufacturing cost. The metric can be used in comparison status as an indicator for profitability per product family over a period. Positive high values of PFP indicate profitable product family.

Fig. 2 Evaluation criteria's for solution space capability



Configuration variable profitability (CVP), Negative profitability (NPCV), and Skewness of the distribution of profitability (CVPS)

CVP is a metric which is somewhat less trivial to determine. However, if historical configuration data are available with sales price and manufacturing costs registered for each configuration, it is possible to generate a linear model describing the variation in price and cost from the configuration variables using the methods described by Brunoe and Nielsen [15]. From the significance and coefficients for each variable, it will be indicated if a specific configuration choice is profitable, e.g., a specific color. However, assessing each variable may be useful in solution space development choices but less useful in assessing a company's overall capability, since it will consist typically of hundreds of records, corresponding to the number of configuration options. However, once the profitability for each option is calculated, the distribution of profitability's may be analyzed. What is interesting here is how many configuration variables (percentage) have negative profitability (NPCV). Obviously, this value should be as low as possible and will indicate how well a company is able to develop only configuration choices, which are beneficial. Furthermore, we propose a metric for the skewness of the distribution of profitability (CVPS). A positive value of CVPS will indicate that a few configuration variables are very profitable, whereas a negative value of CVPS would indicate that a number of configuration variables contribute significantly to a lower profitability, specifically for these above-mentioned metrics, and because they are calculated based on algorithms, no arithmetic equations have been included.

Used variety (UV), mean configuration variable utilization percentage (MCVUP), and configuration variable utilization percentage variance (CVUPV) source: [14]

$$\mathrm{UV} = \frac{\text{Number of perceived variants}}{\text{Number of all possible variants}}$$

UV metric addresses how well the solution space is utilized by the customers, i.e., how much variety is offered vs. how much does actually make sense compared to the customers' requirements. However, using this metric may be difficult in practice, since the number of perceived variants is not readily available. A more practical way of assessing the utilization would be to calculate the frequency by which each configuration variable is chosen by a customer. By dividing this by the frequency of which configurations are made in general, the percentage of configurations containing a certain configuration choice could be calculated, thereby describing the utilization of a certain configuration variable. If these percentages are analyzed statistically, the two metrics MCVUP and CVUPV can be derived. The value of these two metrics can provide insight into the magnitude and differences in frequency by which certain parts of the solution space are actually creating value for customers. Because they are calculated based on algorithms, no arithmetic equations specific for MCVUP and CVUPV have been presented.

Repurchase rate (RR) source: [11]

$$\mathrm{RR} = \frac{\text{number of repurchases}}{\text{total number of purchases}}$$

The metric RR describes to what extent customers repurchase a product, or to what extent customers return to the company to buy a different product. If customers repurchase products regularly, it is reasonable to assume that those customers have been happy with the variety and the product in general. Otherwise, they would likely have chosen a competing product instead.

A high value of RR can be interpreted as an indicator for high customer satisfaction with the product offerings, including variety. Clearly, the RR does only make sense for products, which are purchased frequently, e.g., customized muesli or shirts, whereas products like cars or houses are purchased less frequently by the same customer, rendering this metric irrelevant.

Configuration Abortion Rate (CAR) source: [10]

$$\mathrm{CAR} = \frac{\text{number of aborted configurations}}{\text{number of initiated configurations}}$$

The value of CAR (same as CA metric presented in Sect. 2.1) can also be a measure of how satisfied the customers are with the offered variety. If a customer initiates a configuration and is not able to select the desired product properties and is thus unsatisfied with the offered variety, that customer is likely to abandon the configuration and purchase a competing product. Hence, a high abortion rate could indicate that customers are dissatisfied with the offered variety and vice versa.

Multiple use (MU) source: [16]

$$\mathrm{MU} = \frac{\mathrm{NV}}{\mathrm{NM}}$$

The value of MU metric indicates how many modules are required to produce all variants within the solution space [17]. NV is the number of product variants required by customers and NM is the number of different modules required to build all variants in the product portfolio. While number of different modules should be easy for any company to determine, the number of variants required by customers is less trivial.

Modules Commonality Metric (MCM) and Parts Commonality (PC) source: [10]

$$\mathrm{MCM} = \frac{\text{Number of common modules}}{\text{Total number of different modules}}$$

The MCM [18] is a measure of how many modules are common to all variants relative to the total number of different modules. Generally, a higher MCM value will indicate more efficient product architecture, since higher commonality will usually imply lower manufacturing and development costs source: [10].

$$\mathrm{PC} = \frac{\text{Number of common parts}}{\text{Total number of different parts}}$$

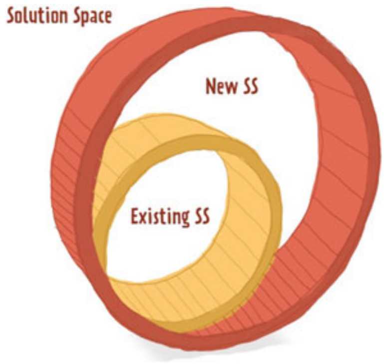
PC [18] is used to measure the relationship between common parts and the total number of different parts in the same way as the MCM. A high PC value also indicates an efficient product architecture since that would imply higher purchasing volume for each different part further implying lower purchasing costs.

Rate of which New Configuration Attributes are Introduced (RNCA), Rate of Eliminated Configuration Attributes (RECA), and Average lead time for configuration variable changes (ALCVC)

RNCA [14] is determined by summing up the number of added configuration choices during a certain period. Similarly, the value of RECA can be measured [14]. A high RNCA value indicates that a company frequently introduces new options for customers and would indicate that the company reacts to a broad spectrum of changes in the market. A large difference between RNCA and RECA would indicate that the solution space is either growing or shrinking. A steadily growing solution space could indicate a problem, since the company may be focusing on introducing new variety without doing “housekeeping” and eliminating options not needed anymore. This could result in unnecessarily increasing manufacturing complexity.

The two metrics described above describe the change rate of the solution space, but not the lead time for changes (ALCVC), which is also essential when

Fig. 3 Evaluation criteria's for robust process design



competing in a rapidly changing market [14]. Specific for these above-mentioned metrics and because they are calculated based on algorithms, no arithmetic equations have been included.

2.3 Robust Process Design Metrics

To evaluate metrics in Robust Process Design, two viewpoints have been introduced and are indicated in Fig. 3.

- The ability to manufacture a variety of products within a fixed solution space, i.e., the current product portfolio/variety—*Robustness toward existing variety*
- The ability to adapt the manufacturing system to accommodate new variety, e.g., when the solution space changes due to new product options—*robustness toward new variety*. This has a close relation to solution space development.

Both viewpoints of the capability are relevant; however, they are not necessarily correlated. For example, a purely manual production is highly flexible toward new variety compared to a highly specialized and automated production, whereas the latter would probably be more efficient in manufacturing a predefined variety.

Differentiation point index (DPI) source: [19]

$$\mathrm{DPI} = \frac{\sum_{i=1}^{n} d_i v_i a_i}{\mathrm{nd}_1 v_n \sum_{i=1}^{n} a_i}$$

v_i # of different exiting in process i
n number of processes
v_n final number of varieties offered

d_i average throughput time from process i to sale
d_1 average throughput time from beginning production to sale
a_i value added at process i

It is generally acknowledged that a late differentiation point or customer decoupling point is an enabler for an efficient mass customization production, the DPI is a measure of how postponed the variant creation is in a manufacturing process. DPI indicates the postponement of variants and on the other hand how many manufacturing processes have to change due to product variety. The most postponed manufacturing setup is expected to support highly robust manufacturing processes and therefore a very good indicator of robust process design.

Setup index (SI) source: [19]

$$\mathrm{SI} = \frac{\sum_{i=1}^{n} v_i c_i}{\sum_{j=i}^{v_n} C_j}$$

v_i # of different exiting in process i
n number of processes
v_n final number of varieties offered
C_j Total cost of Jth product
C_i cost of setup at process i

SI indicates how setup costs contribute to the overall manufacturing costs. The SI calculates the cost of setup of manufacturing processes compared to the total cost of a product. Since a high value of setup cost is an indicator of a low robustness, this indicator can contribute to the assessment of process robustness.

Quality of order reception (QOR) source: [20]

$$\mathrm{QOR} = \frac{\#\,\text{of orders delivered on time} \cap \#\,\text{of orders with zero defects}}{\text{total}\,\#\,\text{of orders}}$$

The metric QOR indicates how well the production performs in terms of on-time delivery and the defect rate.

Number of different modules manufactured per process (NMP) source: [21]

$$\mathrm{NMP} = \frac{\sum_{i=1}^{n} m_i}{n}$$

m_i # of different modules manufactured at process i
n # of different processes

NMP gives a measure of the average number of modules manufactured in the different manufacturing processes. A higher value of NMP will indicate robust processes, since each process will be able to manufacture more different modules and thus a higher number of end variants.

Degree of manual labor (DML) source: [21]

$$\mathrm{DML} = \frac{\sum_{i=1}^{n} \frac{\mathrm{lc}_i}{\mathrm{tc}_i}}{n}$$

lc_i labour cost for manufacturing product i
tc_i total cost of manufacturing product i
n # different products

The metric DML can be used as an indirect indicator of process robustness, since a low value of DML indicates less need for manual processing, which again indicates that the non-manual manufacturing processes are able to supply a high variety.

Process variety increase (PVI) source: [21]

$$\mathrm{PVI} = \frac{\sum_{i=1}^{n} p_i}{n}$$

p_i # of new processes introduced for product option i
n # of new product options in the period

PVI indicates how much the variety of manufacturing processes increases when a new product option or product is introduced in the manufacturing system. The PVI metric calculated as an average during a period in time. A low value of PVI will indicate a high robustness since this implies that few new processes need to be introduced, when a product option is introduced and thus that the existing processes can accommodate new product variety.

Capacity expense increase when introducing a new option (CAPIV) source: [21]

$$\mathrm{CAPVI} = \frac{\sum_{i=1}^{n} \mathrm{cap}i_i}{n}$$

capi_i Percentual CAPEX increase from introducing product option i
n # of new product options in the period

In addition to the PVI metric, the CAPIV is introduced. This is done since a high value of PVI does not necessarily can be compared with high cost, given a new process is implemented on existing flexible equipment. The CAPIV metric also calculated as an average over a period of time.

Time to introduce a new option in the manufacturing system (TIV) and cost of introducing a new option in the manufacturing system (CIV) source: [21]

$$\mathrm{TIV} = \frac{\sum_{i=1}^{n} \mathrm{ti}_i}{n}$$

ti_i time from product design finish to manufacturing system ready
n # of new product options in the period

$$\mathrm{CIV} = \frac{\sum_{i=1}^{n} \mathrm{ci}_i}{n}$$

ci_i cost of introducing product option i
n # of new product options in the period

The time and cost to introduce new product variety are also important metrics to assess process robustness, since robust processes will imply low cost and fast introduction of new product variety.

3 Discussion

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most mass customization companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability. If for instance the profitability of the solution space changes, instead of changes in the solution space, it could be due to changes in the manufacturing processes lowering manufacturing costs or changes in choice navigation leading customers to choose products sold at a greater price.

One other example is the metric configuration abortion rate which we argue indicates how well choice navigation is implemented. However, the configuration abortion rate will be strongly influenced by the solution space, i.e., how well the offered variety matches the demanded variety. In future research, the relationship between the capabilities should be established and the links between all three capabilities need to be analyzed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

When performing an assessment and interpreting the values of the metrics, the interpretation should take into account the product type. Also when benchmarking, companies manufacturing different products cannot necessarily be compared directly. The reason for this is that several metrics are based on the customers' actions, and these actions will depend on the product type. For example, a customer buys a customized car compared to a customized bag of muesli, the customer would probably then be more likely to complain or return the car if it has a wrong color compared to the muesli, if a wrong ingredient has been added. In that case, the difference would be due to the difference in cost of the products. Furthermore, a metric like the repurchase rate makes more sense for some product types than others. For example, customers are likely to repurchase muesli more often than cars. So this metric would depend on to what extent a product can be characterized as a consumable or a durable, and in case it is a durable, how long the life cycle is.

4 Conclusion

In order to support the development of production in mass customization, metrics are needed in order make performance measurement, assessment, and benchmarking. To establish these metrics, relevant literature has been reviewed and several applicable metrics have been identified. Further metrics have been defined in areas where no sufficient metrics could be identified in literature.

In relation to research in mass customization, it is the intention to apply these metrics in different types of mass customization companies to analyze what distinguishes successful mass customizers. It is the intention that these metrics can be used in mass customization companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve.

This work concludes a preliminary research of assessment and measurement of the mass customization process. We have with this paper finalized a general approach how to assess and measure mass customization and set a framework of potential metrics, whether this is for the purpose of internally performance indicators or it is used for benchmarking in general. The next stage in this research will be test and evaluation of these potential useful metrics.

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Mass-Customization Service Encounters: The Influence of the Co-Design Process Structure on Performance

Miriam Oversohl and Moritz Wellige

Abstract Increasingly, companies offer customizable products to consumers. This study investigates how the different layouts of a co-design process affect customers' perception and evaluation of the process and its outcome as well as the productivity of the process from the companies' point of view. In an experiment which was carried out with a mass-customization provider in the field of shoes, the authors find that a more structured co-design process reduces customers' perception of complexity and decreases time duration necessary to serve customers. However, some expected effects could not be confirmed in the experiment. More specifically, the modifications show no effect on outcome variables like customer satisfaction. Nevertheless, this study provides some valuable implications for how companies can design their co-design processes to increase the productivity and decrease complexity.

Keywords Co-design process · Customer interaction · Service encounter · Productivity · Complexity

1 Introduction

Mass-customization (MC) business strategies require information to be exchanged between the MC provider and its customers. These providers have to communicate customization options, and customers need to articulate their preferences [1].

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During this interactive co-design process, a product that matches customers' needs has to be found, which is feasible within production possibilities [2]. However, this process of identifying suitable product solutions is associated with difficulties and high effort for companies as well as for customers [3]. The associated high degree of variety in the assortment as well as the co-design process itself can induce complexity and uncertainty for the customers [4]. If customers' uncertainties and efforts of choice making are too high, they might cancel the purchase [5]. Thus, designing a co-design process requires companies to balance customer requirements concerning the co-design process, costs, and efforts in order to gain a high level of productivity and customer satisfaction at the same time.

This study investigates how a modification of the co-design process influences perceptions of complexity and the overall productivity of the MC provider. Therefore, an experiment with 79 participants was conducted, using an MC provider in the field of luxury shoes as example. An analysis of companies' co-design process, a focus group with its customers, and an interview with the CEO indicates that the mentioned difficulties and efforts associated with co-design could be identified in the company: They need to invest one hour of time on average to co-design a pair of shoes together with its customers. Moreover, during the co-design process, technical devices and other resources of the company are tied to the service process. Thus, the present layout of the co-design process of the company is associated with high expenditures and costs to serve each single customer. In the focus group, it was investigated that customers are often overwhelmed by the co-design process and the product options the company is offering. Particularly for novices, the co-design process seems to be a tough task.[1]

In an experiment, the transparency of the co-design process, its structure, and outer appearance of the store's environment were manipulated in order to investigate effects on customers' perception and evaluation, and the overall productivity of the process. Therefore, basing on the theory, hypothesis will be deducted in the following. Subsequently, the data acquiring and analysis will be described. Finally, results will be presented and managerial implications and limitations of this study will be discussed.

2 Theory and Hypotheses

MC providers face the challenge to design the MC service encounter in an appealing manner. One issue of concern is complexity that is often associated with variety [6] also called the "paradox of choice" [7]. Whereas, on the one side, customers value variety as finding a suitable product solution is more likely within a large assortment, and on the other side, variety fosters complexity and in turn impedes customers' decision-making process. Amount of customization

[1] This study is part of the research project KUMAC (http://www.kumac.de/).

possibilities and related information might appear quite complex and confusing [5, 8, 9]. Search and information costs rise due to the large amount of alternatives that have to be evaluated.

Companies need to ensure that customers are able to enjoy a sufficient degree of freedom during the configuration while minimizing the risk of mass confusion [10]. Reducing complexity within the MC offering is presumed to create value for customers as well as for companies. The co-design process structure and the outer appearance of a store contribute to perceptions of complexity. The aim is to construct MC environments that satisfy customers' needs, reduce complexity and uncertainty, and simultaneously increase operational ease and efficiency from companies' point of view [11].

In the following, it will be hypothesized how a more transparent structure of co-design processes and better-tuned outer appearance of the environmental process surroundings, thus more customer-oriented processes, affect the different determinants of customer satisfaction and the productivity of the overall co-design process.

2.1 Duration of the Co-design Process

Defining a customized product is more time-consuming than choosing a standard product off the shelf [3]. Customers need to get familiar with the MC concept and evaluate various individualization options. This requires time as customers want to ensure that they recognized the entire offering and collected all relevant information [9]. To reduce anticipated regret and uncertainties, customers spend extensive time within the decision-making process. Empirical results confirm that emotionally difficult decisions impede decision-making and demand more time [12, 13].

The service encounters' environment affects customers' decision-making process [14]; interior can contribute to customers' reconstruction of the co-design process as indications about the service procedure can be given [11]. Customers value stores that follow a logical structure and provide assistances (e.g., signs or separated waiting areas) to comprehend the offered service more easily [14]. In the context of MC creating transparency within the co-design process and aligning, the outer appearance of a store with the co-design process seems to create value. The layout of a physical shop environment can be used to guide customers through an assortment [15]. An organized structure, which reflects the co-design process, is supposed to facilitate customers' decision-making. Customers are supposed to process the co-design process more easily if it follows a logical structure. In turn, the co-design process should demand less time.

H1 The co-design process will demand less time within a more customer-oriented co-design process.

2.2 Process Effort and Enjoyment

Customers are willing to pay premium prices for customized product solutions as MC providers succeed in creating pleasurable shopping experiences [16]. It seems crucial that customers enjoy the configuration task and do not perceive the co-design process as a waste of time [1]. Customers experience different values from the co-design process. They are proud to be the initiator of the customized product, also called the "I designed it myself" [17], or the "pride of authorship" effect [3]. Furthermore, customers enjoy venting their creativity [18].

The design of the MC service encounter should contribute to customers' outcome of the co-design process; process effort and process enjoyment are of concern. Whereas process effort should be minimized, customers' joy should be maximized [19]. Perceived complexity has a major impact on those two items. Within a complex environment, it seems to be even more difficult to define a customized product [5]. A wide range of customization possibilities can confuse and overwhelm customers [9].

Precise directions and simple layouts are in need to support customers accomplishing the transaction [14]. The aim is to facilitate customers' decision-making. Transferring findings from the MC online environment to the stationary retail, it seems valuable to structure the configuration task hierarchically [20]. It is anticipated that a transparent co-design process that is aligned to the service environment can be passed more easily. Customers are able to complete the configuration task on their own, what in turn raises feelings of accomplishment and increases satisfaction [3].

H2a Customers perceive less complexity within a more customer-oriented co-design process.

H2b Customers perceive higher process enjoyment within a more customer-oriented co-design process.

2.3 Product Satisfaction

Besides values stemming from the co-design process, customers perceive further values from the final product itself. Functionality and utility are enhanced as products are aligned to customers' needs [4]. How satisfied customers are with the product outcome depends on the degree to which needs and expectations are met [21]. If expectations are fulfilled, customers are contended.

Research proved that product satisfaction is connected to process experiences [18]. Customers, who perceive the co-design process as entertaining task, evaluate the final product more positively and are willing to spend more money [22]. Furthermore, an easy process is supposed to create value as customers presume to make the right choice; due to convenience of the decision, they perceive less anticipated regret [23]. Thus, a joyful and comprehensible co-design process increases product satisfaction. A transparent co-design process should increase experienced joy and in turn product satisfaction. Furthermore, it is expected that the outer appearance of the MC service encounter has an effect on product satisfaction. Bitner showed within an empirical study that the organization of a working environment influences customers' perceptions of service failure [24]. Disorganized working places were connected to incompetence and inefficiency, and customers within the disorganized treatment considered future appearance of service failures as probable [24]. Thus, physical surroundings appear to contribute to perceptions of service quality and trust. An organized appearance of MC providers is essential as participating within customization demands for a high level of trust. An ordered co-design process should make contribution to perceptions of organization and in turn lead to higher product satisfaction.

H3 Customers perceive higher product satisfaction within a more customer-oriented co-design process.

2.4 Loyalty

Concerning the success of an MC offering, customers' loyalty seems to play an important role. To be successful in the long run requires that customers return to the offering and recommend the company to others [25]. Customers, who are satisfied with an offering, will repurchase and convince others of the company; this phenomenon is termed "word-of-mouth" communication [21]. Certain things account for loyalty: satisfaction with the co-design process, satisfaction with the final product, and the overall impression of the offering. Research proved that service environments have an influence on WOM communication [26]; store remodeling affects customers' tendency to recommend the company at least in the short run. As modification of the co-design process is supposed to enhance process enjoyment and product satisfaction, it seems logical to assume that in turn customers' loyalty will be improved.

H4 Customers show a higher loyalty toward the MC provider within a more customer-oriented co-design process.

2.5 Productivity

To evaluate the overall productivity factors that contribute to productivity have to be identified. The conventional productivity concept needs to be extended to a company–customer perspective. This could be differentiated between two dimensions: the operational productivity and the customer productivity. From the companies' point of view, there are common inputs like hour worked, amount of materials, or use of technical devices [27, 28]. Further, process and personnel issues determine providers' productivity in the special case of MC. Companies' output is specified by the number of closed sales or sold products [29]. From customers' point of view, productivity of the co-design process is influenced through various determinants. Inputs that come into play are time, effort, prior knowledge, creativity, motivation, and decision-making ability. Customers' outcome is affected through satisfaction with the process and product solution, perceived quality, and values stemming from individualization.

Providers face the challenge to use resources efficiently and maximize productivity. The provider's aim is to keep the input as low as possible while maximizing customers' output. Within this experiment, a productivity ratio containing companies' and customers' inputs and outputs before modification of the co-design process will be compared to a productivity ratio after modification of the co-design process. On the basis of the foregoing considerations, it seems plausible that the modification of the co-design process structure affects companies' and customers' inputs and outputs.

From the companies' perspective, the time the co-design process takes is crucial as resources are bonded for the specific period of time. Employees have to be present, and materials and technical devices have to be available. Concerning hypothesis one, a reduction in the length of the co-design process leads to an improvement of productivity for MC providers as the amount of required inputs decreases. Assumptions of hypothesis four have further a positive influence on companies' productivity. As customers are loyal to the MC provider, they are likely to repurchase in the future and recommend the company to others. The process' output rises due to a greater extent of sold items. As inputs decline and outputs increase through the modification of the co-design process, operational productivity improves.

From the customers' point of view, the modification of the co-design process structure is as well assumed to increase productivity. In terms of hypothesis one, less duration time of the co-design process leads to an improvement of productivity as customers have to spend fewer inputs. Besides process' outcomes increase, customers perceive higher process enjoyment and product satisfaction. Changes in the operational and the customer productivity affect the overall productivity of the MC service encounter. Following the previous assumptions, modifying the co-design process structure yields an improvement in the both dimensions of the productivity ratio. Therefore, it seems plausible to hypothesize that the overall productivity improves as well.

H5a Operational productivity is higher within a more customer-oriented co-design process.

H5b Customer productivity is higher within a more customer-oriented co-design process.

H5c The overall productivity is higher within a more customer-oriented co-design process.

3 Data and Research Design

Within an empirical experiment, influences of a modification of a co-design process in terms of customer-orientation will be examined. In detail, it will be examined whether the co-design process structure has an impact of MC service encounters productivity. Data collection, analysis, and results will be presented.

Store Selection As already mentioned, the study was conducted together with an MC provider in the field of luxury shoes. Results of the focus groups displayed that customers sometimes are confused and overwhelmed by the large amount of customization possibilities and different visible stimuli. Therefore, within a first step, the status quo of the co-design process as it proceeds within the store and the outer appearance of the store were recorded. As the status quo had been analyzed, appropriate modifications of the co-design process structure were identified, and a concept for a more customer-oriented co-design process, thus a more transparent and better-tuned outer appearance of the process, was derived.

Design and Procedure Hypotheses were tested using a between-subject design with one manipulation namely modification of the co-design process structure (current vs. modified). The study took place within a research laboratory at RWTH Aachen University. The company provided all materials to rebuild the co-design process within the laboratory environment. Participants separately had to pass the co-design process and afterward complete a questionnaire. Eighty-one women participated within the study; they were randomly assigned to one of the both treatment groups.

Each appointment proceeded in a similar way. After the welcoming, the concept of the company and the procedure of the co-design were explained. Concerning the explanation of the co-design process structure, both treatment groups differed (current co-design process vs. modified co-design process). In the following, subjects had to design their individual shoes. As configuration of the shoes was complete, participants were asked to take part at the survey. Finally, subjects were said goodbye.

Independent Variable The independent variable alludes to the modification of the co-design process (current co-design process vs. modified co-design process).

The current co-design process proceeds similar to the co-design process at the store of the company. Modifications dealt with the structure of the co-design process (transparence) and the outer appearance of the physical surrounding. Concerning structure, the modified co-design process is broken down into minute steps that follow a precise order. In terms of the outer appearance of the environment, the amount of visual stimuli was reduced. Taking leathers as example, the number of patterns was reduced. Whereas in the current co-design process, all possible kinds and colors of leathers were displayed; within the modified co-design process, there was just one pattern for every kind of leather in a neutral color.

Measures Time duration was measured observing the time the co-design process takes place. Process effort, process enjoyment, product satisfaction, and loyalty were measured using a questionnaire. Appropriate scales were adapted from previous studies [9, 18, 22, 25]. Besides, the questionnaire entailed a manipulation check to examine whether the independent variable was manipulated successfully. All five items yield alpha values greater than 0.70 referring to a satisfactory degree of reliability. An EFA was conducted for each variable, factor loadings were above 0.06.

4 Analysis and Results

Seventy-nine completed questionnaires could be gathered and used for further analyses. Statistic methods were applied to assess whether the modification of the co-design process structure yields to variations in time duration, process effort, process enjoyment, product satisfaction, loyalty, operational productivity, customer productivity, and the overall productivity.

Results of the analysis reveal that the manipulation of the independent variable has been successfully made. There is a significant difference between the two conditions in terms of process structure (t (77) $= -2.176$, $p < 0.05$); participants within the modified co-design process experience the co-design process as more structured than participants within the current co-design process condition.

Concerning the duration of the co-design process, it was found that participants within the modified co-design process take significantly less time to complete the configuration task (t (65.55) $= 4.628$, $p < 0.01$). Whereas on average, the current co-design process took 34 min (SE = 0:12:02), the modified co-design process lasted 23 min and 35 s (SE = 0:07:30). Results support hypothesis one; modification of the co-design process led to a reduction in the time duration of about 32 %.

There was no significant difference between the groups in terms of process effort (F (1.77) $= 0.079$, $p > 0.05$); hypothesis 2a could not be confirmed. Subjects did not perceive less complexity within the modified co-design process than customers within the current co-design process. Besides, there was no support for hypothesis 2b. Experienced joy did not differ significantly between the current and the modified co-design process conditions (Welch (1.60) = 0.218, $p = 0.642$).

Subjects within the modified co-design process group were supposed to be more satisfied with the final product solution. Assumptions could not be verified; relevant means did not differ significantly (F (1.77) $= 0.854$, p > 0.05).

In terms of loyalty, there were no statistical differences between the two conditions (Welch (1.67) = 0.277, $p = 0.600$). Customers did not show a higher loyalty toward the MC provider within the modified co-design process than customers within the current co-design process.

Modification of the co-design process was further supposed to increase operational productivity. Results show that even if the output remains at a constant level, reduction in required inputs leads to an enhancement of operational productivity; hypothesis 5a could be supported. Concerning customer productivity, similar results can be documented. As the co-design process took less time, customers have to spend fewer inputs. Outputs were not affected through modification of the co-design process. Although overall customer productivity is higher within the modified co-design process than within the current co-design process, there is support for hypothesis 5b.

As modification of the co-design process improves companies' as well as customers' productivity, the overall productivity of the MC service encounter is also enhanced. Hypothesis 5c could be supported.

5 Conclusion and Future Research

At least for the case of the regarded MC provider, this experiment suggests that the layout of the co-design process has an influence on perceptions of complexity and the MC service encounters' productivity. Modifications in terms of transparency of the co-design process, its structure, and the outer appearance of the store's environment yield to a reduction in perceived complexity and duration time, and thus can help improve the overall productivity. However, the theoretically deducted and hypothesized relationships between the layout of co-design processes and customers' process effort, process enjoyment, product satisfaction, and loyalty could not be confirmed in this experiment. This might reflect the reality, but could also be attributed to the setup of the experiment, such as that manipulations might be not appropriate or some factors that influenced the results were not taken into account. We suggest that further research has to be carried out to verify these results.

However, some of the results offer insights for other MC providers. Although each customization offering is highly dependent on individual product characteristics, most providers face similar problems: Presenting customization options and creating a pleasurable shopping experience for different types of customers are quite difficult. Presentation of MC assortments bears risks of oversupply of visible stimuli and non-transparency within the co-design process. Here, this study offers some valuable hints to other MC providers, how to improve present co-design processes or implement more customer-oriented processes. Results of this case study suggest that MC providers should aim to construct a transparent and evident co-design process. How the structure of a co-design process and the outer appearance of a store can be improved, is shown exemplarily within the experiment. Subdividing the configuration task into minor steps that follow a specific order is supposed to create value. Customers can concentrate on the co-design process and get a better overview about the whole co-design process. Concerning the outer appearance of a store, it appears promising to organize the assortment's structure. Results suggest that it is crucial to ensure that customers are able to handle the amount of visual stimuli. Assigning attributes to superior categories and thereby reducing the amount of presented items promise added value for both customers and providers.

But, due to the nature of experiments, the generalizability of these results is limited. Since this study represents a first experiment on effects of designing more customer-friendly co-design processes in offline environments, it was not possible to control all determinants and factors. We carefully selected the factors to be manipulated. However, we cannot rule out any interaction or confounding effects between the included factors or with other factors that were not taken into account. Further research is necessary to get a better understanding about effects and determinants of co-design processes and how they can be designed more customer-oriented. The study could be repeated containing a within-subject design where participants compare both the co-design processes. Furthermore, for the sake of generalizability, additional experiments should be carried out within other product categories and different markets. Furthermore, it should be displayed whether results can be transferred to the business-to-business context, where consumers have a deeper insight into product attributes due to their professional expertise.

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Mechatronic Behavior Analysis of a Customized Manufacturing Cell

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Abstract Analyzing the mechatronic behavior of a manufacturing cell used in a customized manufacturing process is a difficult task with numerous obstacles. Therefore, a method that can be easily used for developing and optimizing a customized manufacturing cell, i.e., universal contacting module (UCM) cell, for the in-circuit testing of electronic modules is desired. In this paper, we present a convenient method using multi-domain simulation tools for analyzing the mechatronic behavior of the UCM cell. The UCM cell, which consists of mechatronic components such as a six-axis industrial robot and conveyor systems, were successfully modeled, simulated, and validated under several payloads. This work also presents a modeling procedure that can be applied by system engineers with a basic background in control systems for analyzing the mechatronic behavior of manufacturing cell components.

Keywords Mechatronics · Product development · Modeling · Customized manufacturing systems

1 Introduction

The need for product customization drives the manufacturing industry to search for an effective and efficient method for the development of flexible manufacturing cells. Unlike a mass production system that produces only a few variants of the product, industry requires attention to many product variants that are produced for a short period of time [1]. Therefore, a customized manufacturing cell should be able to be used for several variants of a product at the same time. Furthermore, a

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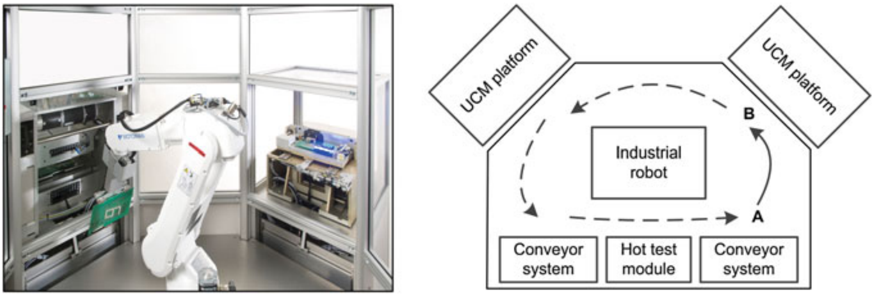

Fig. 1 The UCM cell (*left*) and the layout of the cell (*right*)

manufacturing cell itself is a complex mechatronic system, which consists of mechanical, electrical, and automatic control systems. This leads to the development of a customized manufacturing cell as a complex task with many obstacles.

The most powerful method that has been commonly used by industries and researchers for developing and analyzing mechatronic workcells is a modeling and simulation approach [2, 3]. Many papers about the simulation of manufacturing cells have been published; however, most of them are still based on a specific physical domain. This makes the analysis and optimization processes time-consuming and cost-intensive. On the other hand, most simulation tools that are already used in the market for analyzing a mechatronic system are relatively expensive. To address that issue, we use the free multi-domain simulation tool, OpenModelica,[1] and the commercial package, Wolfram *SystemModeler*,[2] for developing and analyzing the mechatronic behavior of UCM cell components.

The UCM[3] cell is a comprehensive test platform for testing electronic devices, which is used for checking electronic modules (printed circuit boards). This cell consists of a six-axis industrial robot with special grippers, two small conveyor systems, two UCM platforms for in-circuit testing and functional testing of electronic components, as well as a hot function test module (see Fig. 1). The interesting issue concerning this cell is how to expand the application of the UCM for other electronic components that have different weights, and to choose suitable parameters to optimize the process. Therefore, the modeling of the UCM cell components is performed under several payload weights. Thus, we can choose the right parameters for various UCM operations.

Accordingly, the aims of this research are to analyze the system performance of UCM cell components (a six-axis industrial robot and a conveyor system) under different payloads. Furthermore, we used the results from this research for

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[1] OpenModelica is an open-source Modelica-based modeling and simulation environment developed and supported by the Open Source Modelica Consortium (OSMC) and Linköping University (LiU).

[2] Wolfram *SystemModeler* is a trademark of Wolfram Research, Inc.

[3] UCM is a trademark of IMAK GmbH.

analyzing the energy consumption of a manufacturing system, especially for the six-axis industrial robot. This paper also presents the modeling procedure of mechatronics systems for system engineers with a basic background in control systems using multi-domain software tools. In addition, a comparative study in OpenModelica and Wolfram *SystemModeler* is discussed at the end of this paper.

Both OpenModelica and Wolfram *SystemModeler* are simulation tools based on the Modelica language, which provide a wide variety of mechatronics libraries. These simulation tools are appropriate for simulating a manufacturing cell, which is a multi-domain system. Modelica itself is an open and object-oriented language; hence, the researcher can access the programming code and develop or modify a model library when it does not coincide with the user requirements [4].

There are three main contributions from this paper. The first contribution is a convenient modeling method that can be used by system engineers for developing, analyzing, and optimizing a customized manufacturing cell. The second contribution is a dynamic behavior analysis of mechatronic systems that is part of the manufacturing cell. Results show that the mechatronic behavior (i.e., speed response, acceleration, electric current) is strongly influenced by the payload of the UCM cell workpiece. This data can be used as a reference to choose and optimize the operating parameters of the UCM cell components while improving the productivity of the cell. In addition, we also provide a comparative study between free multi-domain simulation tools and commercial ones. The result of this comparative study will give useful information to system engineers for choosing the right simulation tool in their project.

2 Related Work

Simulation is a key technology for shortening the development time of customized mechatronic systems. This is because it can be used effectively to verify and analyze the characteristics of physical systems [5]. In this study, we focused on analyzing the effect of payloads on the mechatronic behavior of a six-axis industrial robot and a conveyor system, both parts of the UCM cell. The mechatronic behavior in this research refers to the dynamics and electric behavior of UCM components.

Concerning the payload's effect on the dynamics of an industrial robot, there have been many studies conducted. Several researchers present the analysis of initial parameters of the industrial robot load in order to improve the dynamic accuracy of the robot. It was found that the mass, inertia, and the location of the center of the robot's payload are important factors that influence the robot dynamics [6]. Another study also shows the payload influences the robot's performance and its repeatability [7]. In the conveyor system, the weight of the payload strongly influences the performance and dynamic behavior [8]. However, most of these studies are based on an experimental investigations or mathematical calculations to analyze the effect of payloads. For system engineers, these methods are inconvenient and time-consuming. Moreover, the use of multi-domain simulation tools for mechatronic behavior is still rare.

Regarding the energy consumption analysis of mechatronic systems, much research has been conducted, such as in [9, 10]. Nevertheless, analyses based on payload and multi-domain modeling and simulation methods are still limited.

3 The Digital Model of the UCM Cell

In this section, we describe the modeling of the UCM cell components: A six-axis industrial robot and conveyor systems.

3.1 Modeling the Six-Axis Industrial Robot

The industrial robot used in the UCM cell is the Motoman MH5L.[4] It is a small robot platform, which has a 5-kg payload and is commonly used in a wide range of applications, such as packaging, material handling, machine tending and dispensing [11]. While modeling, parameters and specifications (i.e., the maximum speed of every axis, and the weight and inertia of the robot structure) used for the model of this robot are based on the information from [11]. However, because not all robot parameters are available in that reference, the initial parameters from the Modelica library and from the measurement data have also been used. As can be shown in Fig. 2, the robot model consists of path planning, six axes, and the robot structure.

Modeling the robotic system started with creating a motor drive model on each of the robot axes. Every motor drive model consists of axis path planning, a control bus, driver, and servo motor. In this work, the model of the servo motor is based on [12]. Some of these class models are available in the Modelica library. However, we had to choose a correct model with the right parameters because the simulation results are very dependent on how appropriately the model represents the real system. The second step for industrial robot modeling is creating the mechanical structure of the robot. In this step, we use Multi-body components, such as revolute joint and body mass. The next steps are defining the path-planning model and reference point for the robot's position. For the robot's path planning, we use a PTP2 model, which instructed the robot to move as fast as possible from the starting position to the end position under specific kinematic constraints [4]. Finally, the verification of every model is needed in order to ensure that each robot component model represents those of the real world. The equations and the parameters should be managed and ensured so as to have the same number. Thus, a

[4] Motoman is a trademark of Yaskawa Electric Corporation.

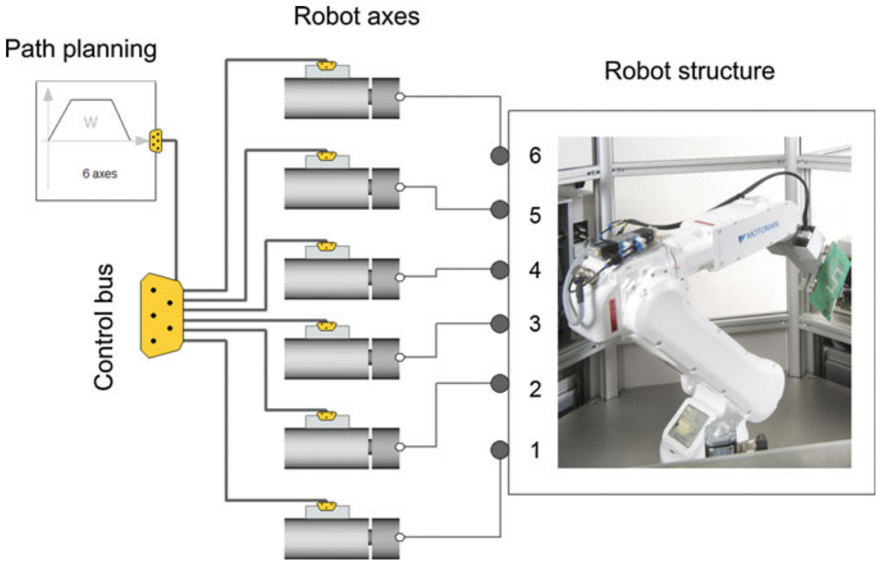

Fig. 2 The model for the six-axis industrial robot with the Modelica-based simulation tool

lot of time and effort are required, especially when using the free multi-domain simulation tool like OpenModelica.

3.2 Modeling the Conveyor System

Modeling and simulation of the conveyor system leads to a better understanding of the conveyor's mechatronic behavior, which helps in the development of suitable controllers and in choosing the best operation parameters. As shown in Fig. 3, the conveyor system consists of a PID controller, a motor, and a conveyor structure. While modeling, we started with making a motor and PID controller model and then formed a conveyor structure. Similar to the industrial robot's modeling, verification is conducted in the final step. In order to choose suitable controller parameters, we used the Ziegler–Nichols method. Based on this method, we define Kp: 1.176, Ki: 0.025, and Kd: 0.00625. Compared to other turning methods, the Ziegler–Nichols method is relative simple and widely used in industries to give better approximations of the controller; therefore, it is suitable for a systems engineer with a basic knowledge of control systems. The Ziegler–Nichols method is explained in detail in [13].

To model the motor, we modified the Modelica library components' parameters and initial values corresponding to the real motor. Generally, the parameters of the motor's model are based on information from [14]. The conveyor structures used as transport systems consist of several components from rotational and

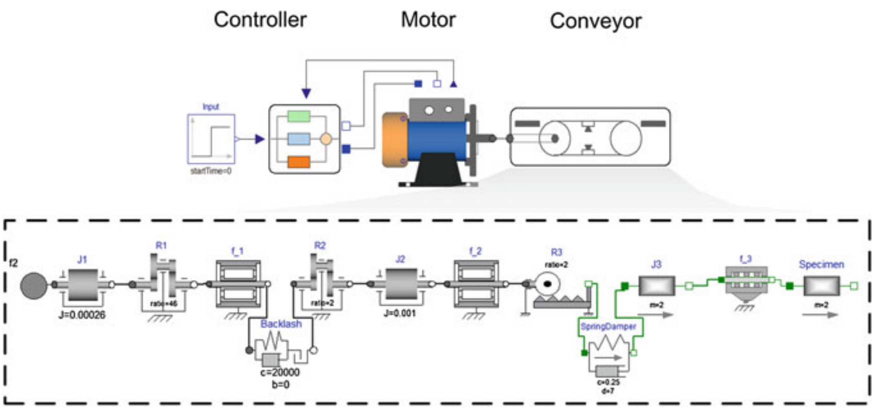

Fig. 3 Model of the conveyor system

translational packages. This structure consists of inertia, reduction gears, bearing frictions, a backlash, spring damper, support friction, and conveyor load. To represent real conditions, a spring damper is modeled using the coefficients c: 0.25 and d: 7. Loads representing the electronic specimens are simulated under several weights, from 1 to 5 kg.

4 Simulation Results and Discussion

4.1 Simulation Results from the Six-Axis Industrial Robot

In this work, the robot is simulated from position A to B (see Fig. 1) with a payload from 1 to 5 kg. The analysis focuses on the sixth axis, due to its high vibration. The results from this simulation are shown in Figs. 4 and 5. In these figures, we plotted torque, acceleration, and position of the sixth axis as well as current of the all robot's motors. As can be shown in Fig. 4, the robot's payload has a significant influence on the robot's dynamic behavior. Heavier payloads lead to an increase in the oscillation of robot's torque (see Fig. 4a). Thus, we see that changing the UCM specimen, which has a different weight than the existing one, results in varying robotic torque. The values from these graphs can be used as a reference to tune the UCM operation parameters in order to improve the dynamic accuracy of the robot. Moreover, they can also be used to verify the control system of the robot.

As shown in Fig. 4c, every kilogram of payload contributes to a mere deviation of about 0.2 milliradians. Although Fig. 4a and b show that the weight of the payload alters the torque and the acceleration, though the accuracy of the robot is not affected. Thus, from the simulation results, it is evident that the robot's system performs sufficiently and robustly for payload variations.

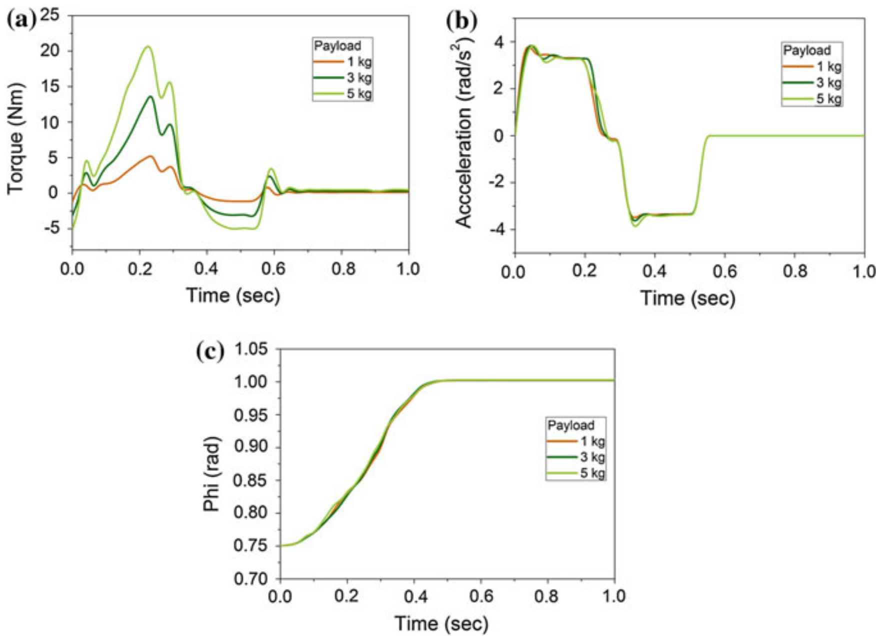

Fig. 4 Dynamic behavior of the robot's sixth axis under several payloads

4.2 Validation and Electrical Behavior of the Industrial Robot

A comparison between the simulation's results and actual measurements is used to validate and analyze the accuracy of the simulation model. In this comparative study, we focused on the electrical behavior of the industrial robot. From the simulation method, we obtained a value of current, resistance, and voltage from the motor of every robot axis. Thus, from the simulation data, we calculated the robot power. While using actual measurements, we obtained data for the current, voltage, and power from the robot. We used the value of the current to conduct a comparative study since this value is directly collected from both of these methods. Comparison results are presented in Fig. 5. The deviation of the robot's current between measurement and simulation is less than 15 %. The deviation is caused by the robot control unit that not modeled since this component is outside of the robot structure. When we add the current value from the robot control unit to the simulation results, it matches well with the measurement values.

Based on Fig. 5, the robot's payload strongly influences the value of the motor's current. The varying payload results in a different current value for every robot axis. Therefore, this data can be used as an indicator for analyzing the energy efficiency of manufacturing components since the current is closely related to power consumption.

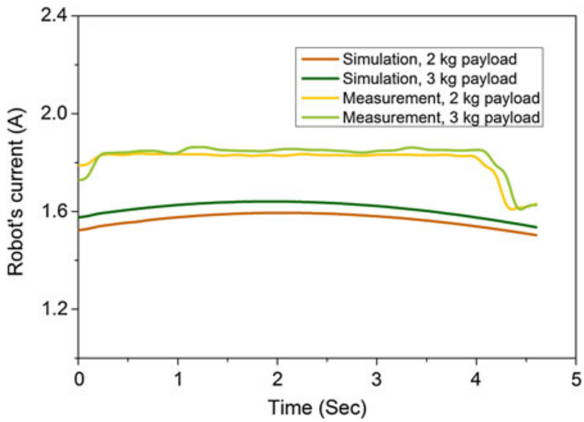

Fig. 5 Current in all robot axis motor under several payloads

4.3 Simulation Results from the Conveyor System

As shown in Fig. 6, the dynamic of the conveyor depends on the weight of the specimens. A heavier specimen reduces the speed and the acceleration response (see Fig. 6a, b). A specimen with 5 kg of weight needs 3 s to achieve a steady response, and with 1 kg of weight, it only needs 1 s. Thereby, the control system of the conveyor has not adapted quickly enough to the heavy specimen. However, these conditions are acceptable when used as a transport system in a UCM cell since the acceleration response is not as high. The simulation results (see Fig. 6c) also show that the torque of the motor is affected by the weight of the specimen. Similar to the speed responses, a heavier specimen reduces the response. However, this condition generally shows that the UCM cell can be used not only for monitoring a single variant of PCBs but also for other variants that have different weights.

Simulation results also show that the backlash and friction coefficient of the conveyor damper have an influence on the speed response. Therefore, for precise applications, a modification of the damper is needed.

4.4 Comparative Study

Based on our experience with this work, we present a comparative study between the open-source Modelica tool OpenModelica version 1.9.0 and the commercial tool Wolfram *SystemModeler* 3.0.2 in this sub-chapter. In this comparative study, we focus on the user interface, simulation results, modeling deficiencies, and simulation time.

- User interface: Both of these tools provide a software template/layout in the same primary theme. A user familiar with OpenModelica will easily adapt to the

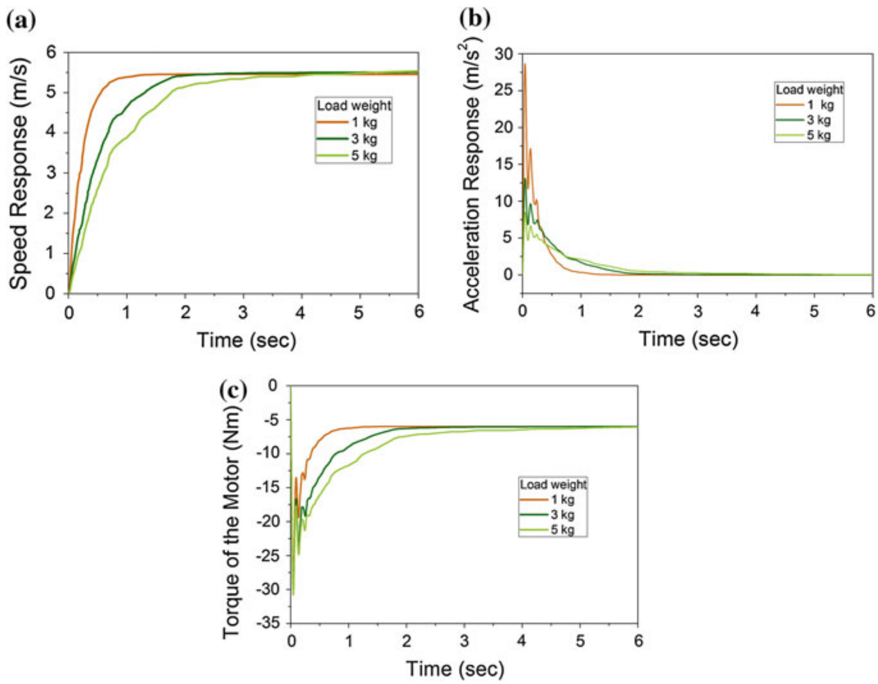

Fig. 6 Dynamic behavior of the conveyor system under several specimen weights

Wolfram *SystemModeler* template. This template is divided into two main windows: modeling and simulation. However, Wolfram *SystemModeler* provides a function that allows the user to more easily create, edit, and simulate the model. Furthermore, Wolfram *SystemModeler* offers more interactive tools to plot and edit the simulation results.

- Simulation results: In this study, we used the DASSL solver, 2-s stop-time for the robotic simulation and a 6-s stop-time for the conveyor system simulation, 0.00001 for tolerance, and an interval setting of 500. From the simulation results, both of these tools produced the same value of graphs.
- Modeling: From the authors' experience, using OpenModelica is relative difficult. With each new model, we always had to verify and check the equations, parameters, and variables. Moreover, some bugs exist in the OpenModelica Compiler.
- Simulation time: For the simulations, we used a standard PC with Intel Core2 Quad processor and 4-GB RAM. Generally, as can be shown in Table 1, when using OpenModelica, we needed more simulation time than when using Wolfram *SystemModeler*. However, this table shows that the time difference is less than 2 min; therefore, for a systems engineer, this issue is hardly crucial.

Table 1 CPU time between OpenModelica and Wolfram *SystemModeler*

UCM components	Industrial robot	Conveyor system
Solver	DASSL	DASSL
OpenModelica CPU time	94.805 s	0.714 s
Wolfram *SystemModeler* CPU time	2.543 s	0.234 s

From this comparative study, we know that for modeling complex mechatronic systems, using a commercial tool is recommended, but for modeling a simple one, OpenModelica is powerful enough. Since OpenModelica is available freely, it is recommended for a system engineering that just wants to know a basic knowledge of mechatronic systems modeling.

5 Conclusion

In this paper, we present a method for the mechatronic behavior analysis of a customized manufacturing cell that is used in electronic production. The method implements the object-oriented and multi-domain simulation tools based on the Modelica language. Using this method, the UCM cell components, such as an industrial robot and a conveyor system, were successfully modeled, simulated, and validated. The procedure for modeling and simulating UCM cell components was also provided in this paper. This procedure can be used to understand the mechatronic behavior for the development and optimization of a manufacturing cell.

The results of the investigation show that the weights of the specimen influence the mechatronic behavior and the performance of the UCM cell components, such as speed, acceleration, accuracy, and torque as well as their electrical behavior. However, from the results, we know that a UCM cell can be used to test several variants of specimen that have different weights. Also, using the results, we were able to optimize the performance and define a strategy for low energy consumption in a UCM cell.

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Modelling and Organising Customer-Driven Business Processes in a Mass Customisation Environment

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Abstract The techniques of mass customisation in the manufacturing area are being challenged by more recent trends of made to order processes. This paper reviews the relevant literature dealing with the challenges of determining specific made to order processes. The researchers then use a case study approach to gain insights into what are the new demands on planners and schedulers. Two case studies in Denmark are highlighted. The researchers found that the tasks of planning business processes in the order flow is likely change in the future as increased adaptation to customer ordering takes place, which will force changes to staff training and company re-organisation.

Keywords Business processes · Modelling · Mass customisation

1 Introduction

In the previous industrial revolution, the custom-made industry went through a transition of standardisation to enable affordable prised products by use of mass production. As an example, there were more than 23,000 custom shoe-making

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establishments in the US in the early 1900, and some twenty years later, barely a few hundred remained, now producing standard-sized shoes [1]. In the 1980s, the competition from low-cost countries put a high pressure on Western industry which led to a much higher degree of customised products. A survey by Lampel and Minzberg [1] found that on average only twenty articles on customisation appeared annually from 1971 to 1980, whereas the number was 234 from 1981 to 1990 and 2,324 from 1990 to 1996.

When changing from mass- to customer-specific production, more departments are involved in order processing [2, 3]. The recent shift towards order-specific customisation has increased the need to control the order process through the administrative business processes in order to secure that the individual orders are delivered on-time and at the right place. Furthermore, companies need to operate within effective supply chain networks that are highly responsive, flexible, innovative and dynamic, while at the same time compressed in order to be able to respond to pressures such as cost reductions, product development, high quality, value-adding products, frequent, on-time deliveries and service [4–6].

In the following possible improvements, options regarding resource consumption, delivery performance and lead-time will be argued when improving business processes and especially by coordinating the activities in the order process and aligning the information flow and use of ICT.

2 Problem Definition

Through the experience of projects in co-operation with industry, a number of general problems related to the interaction and coordination in the order processes of companies have been identified. Generally speaking, the lack of updated and real-time information on for example drawings in production and before this the replenishment needs and the lack of materials necessary in the final assembly of goods are on-going problems for manufacturers. In many engineering industry, the customers are allowed to change the product specification close up to production start and in some cases even after the production has stared. Companies accept all kinds of customer-specific changes, even if this means rework or disposal of previously produced or purchased items. The "customer is king" so the saying goes and many companies do not leave the customer to either select between possible options or else to be charged for the actual costs of the desired product changes. As a consequence, a large number of people in the product development department, purchase, planning and production departments are occupied with customer-specific changes. Furthermore, the number of production orders is growing as batch sizes are reduced. In total, man-hours are increased due to changes caused by customisation.

The product development department in many companies has become a bottleneck because, besides the development of new products, it has to take part in the adaptation of customer orders. Often, the department is not included in the overall resource plan and therefore is constantly behind the production schedule. Errors in drawings and bill-of-materials are not corrected because of the high workload of staff. In the course of time, the workforce in the production department does not report errors because they are not corrected, and a vicious circle is created.

Some information systems have been integrated over time. One example is enterprise resource management (ERP) where financial, manufacturing, shop floor control, scheduling and human resource management are integrated [7, 8], whereas few examples are seen to integrate ERP with, e.g. manufacturing execution systems (MES) and computer-aided design (CAD) systems. This means that bill-of-materials from the CAD system in most cases are entered into the ERP system manually. This is less problematic in a batch environment but highly problematic in a mass customisation environment.

We define this situation as a problem of efficient manufacturing planning, embedding, organising and coordinating the various processes and functions to the continuously updated status of the order. This is a under research area where the literature contributions still is scarce [9]. The conducted case studies have revealed too many changes of responsibility in the order flow and the lack of quality information which causes significant errors and consequent increased workloads. Too much time is spent on searching for information or correcting information as the individual links in the order chain are not fully aware of demands from the rest of the chain.

3 Modelling Customer Order Business Processes

One of the strategies to assist manufacturers in this area is the modelling of business processes. The idea to consider the business processes as a chain is not new. vom Brocke and Rosemann [10] has illustrated the evolution of business process from work simplification towards lean supported by information systems (Fig. 1).

In 1985, Michael Porter introduced his “Generic Value Chain” consisting of five primary activities: “Inbound Logistics”, “Operations”, “Outbound Logistics”, “Marketing and Sales” and “Service” [11]. Besides, the five primary activities four support activities are specified as “Firm Infrastructure”, “Human Resource Management”, “Technology Development” and “Procurement”. Porter’s Generic Value Chain, however, is different from the Activity Chain Model at several points.

Porter only considers one chain for the whole company and places the activity “Order Processing” in the primary activity “Outbound Logistics” and “Production” in the primary activity “Operations”. As “Outbound Logistics” is placed after “Operations”, Porter assumes that the product is produced before the order is processed. In other words, the Generic Value Chain is oriented towards production to stock. This view is also supported by the fact that the “Marketing and Sales” activity is placed after “Outbound Logistics” and thus not integrated with the production and logistics processes.

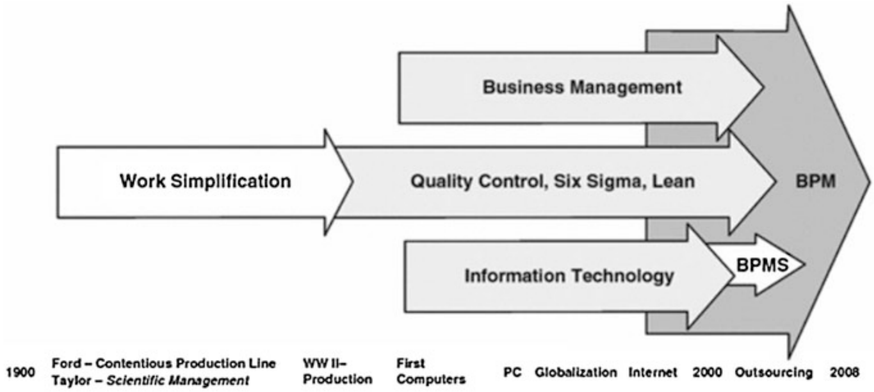

Fig. 1 Illustration of the evolution of business process from work simplification towards lean supported by information systems [10]

As a further development of the Generic Value Chain, Hammer and Champy [12] introduced the business process reengineering (BPR) concept in 1993 bringing customer focus and integration as possible means to increase effectiveness. BPR is based on a total reorganisation of business processes in the company, whereas the Activity Chain Model is focused on the customer order processes.

As discussed in Sect. 1, customised production involves a large number of departments in a functionally organised company. This makes it very difficult for the company in general and for individual employees to obtain the actual knowledge of customer order processes. One purpose of modelling customer-specific order processes is to analyse and communicate the obtained knowledge throughout the company. Subsequently, the model is used to improve current business processes.

To analyse the customer-specific order processes, we recommend a bottom-up approach where all sub-tasks, tasks and information processing performed in connection with customer orders are described. This is done by pursuing orders right from customer contact until the product is delivered and paid. It is important to distinguish among the different types of orders in the company such as standard orders, special orders, urgent orders and spare part orders.

Also a distinction between customer-specific tasks and general/basic tasks is relevant in most companies, especially to identify the relevance (value) of tasks and the cost of customer-specific order processes. This distinction may be difficult, as some activities may be adding value for the company even though the customer is not willing to pay for the activity (order winning vs. order qualifier criteria), for example product documentation or the registration of time consumption in administration and production [13]. Schmid et al. [14] defines non-value-adding information as "information which is not needed instantly or not needed at all". Schmid points out that non-value-adding information (called waste information) will lead to non-value activities such as generation, handling and storage.

Therefore, we make a distinction between customer value-adding activities for which the customer is willing to pay and internal value-adding activities.

It is often relevant to supply the analysis of order processes with the analysis of tasks and information processing regarding the materials flow from reception of raw materials and components through production and assembly to the delivery of final products. This analysis focuses on information controlling the materials flow (such as requisitions, production orders) and on activities (such as receipt and dispatch of materials to/from suppliers and customers, receipt and delivery of materials inside the company). This analysis also gives a thorough knowledge of production processes and of planning procedures on the shop floor. We have observed different objectives in the central planning and in the shop floor planning in many companies, e.g. where central planning focuses on customer orders whereas shop floor planning focuses on utilisation of capacities.

Further, it is important to examine time consumption for several reasons: (a) to evaluate which costs are related to orders and which are related to development. (b) to improve planning and gain information about time consumption per unit and bottlenecks and (c) to evaluate the possible profit of rationalisation.

4 Case Study

One case company, located in Denmark, is a typical example of a company where customers have a substantial influence on the working procedures of order management. An increasing number of customer-specific demands and inquiries cause more work in order management which results in an augmented time consumption of white-collar employees. Some 80 employees work at the case company, and order management is handled in a criss-cross fashion across existing departments and then tasks solved by the departments. All departments are more or less involved in the (nearly) 150 orders, and in the unknown number of inquiries and offers which are dealt with each year. Furthermore, the case company develops products intended for customer-specific alterations far into the order and production process.

A preliminary analysis within the company showed that the time consumption per order was far higher than indicated by costs estimates and that the time consumption overall was increasing, especially for exports. The preliminary analysis provided a basis for a discussion of the company's assessment of time consumption per order and how this has evolved over the years during the transition from being a mass producer to a being a customised order producer.

A more detailed analysis of order management showed that the processing of an order was unclear and involved transfer of responsibility many times. This was supported by later analyses that indicated large time consumption in order management. Moreover, several problems were revealed during the analysis: Drawings were not available in time and product specifications were often completed late in the order processing. Much overtime work and many rush jobs were caused by customer changes. And finally, the errors created a lot of manual paper work and double filing.

An example of one of the more analyses carried out at the company was an analysis of the time consumption of white-collar employees. The purpose of the analysis was to establish the time consumption for each activity: which departments and employees were involved and how much time was spent on value-adding and not value-adding activities. A result of this analysis was among others, that too many departments and employees were involved in each activity, which means that it was necessary to restructure the business processes and the organisation.

The company's order management system was analysed, and the connection between information and activities was documented by IDEF diagrams. Inspired by Laudon and Laudon [15], key business processes and key measures were identified and illustrated. A large number of forms had been added during time, and a closer analysis of the system led to a 50 % reduction in the number of forms used. This first evaluation of collected information in the manual system was an important part of the later reduction in time consumption in order management.

Order management was split into well-defined and limited activities and sub-tasks. Hereafter, the activities were regrouped in other or new sub-tasks and activities. Through working with reorganising order management, it became evident that more employees carried out a number of sub-tasks which could advantageously be grouped in new tasks. Consequently, more sub-tasks were combined in larger tasks. This combination reduced the number of transfers of responsibility, and at the same time, it required that the individual employee had more qualifications. Further, defining the contents of each activity is a good way of revealing old routines and sub-systems which are no longer used, or worse, which are carried out twice.

The interesting is not alone the possibilities for rationalisation, but also the knowledge about the contents, size and distribution of sub-tasks which can be used in further development of order management in the company. Order management will undoubtedly become a more strategic element if customer-specific variants are introduced as a competitive parameter alongside lower prices, shorter lead-time and higher delivery precision. After the conclusion of this case, the company has itself launched three big projects in order to further develop the order management.

- Introduction of a new control concept for order management established as product centres which are organisational units responsible for all customer relevant tasks. The new control concept has contributed to an improved customer contact resulting in a reduction in errors and of time consumption both in the new product centres and in the head office. The saved time in head office has until now been used for development of a new budget system and two new products.
- Development of a new order specification system, which gathered all information from existing documents used for specifying an order. The purpose of this work was to secure quick access to the latest documentation and to reduce time consumption of activities by 25 %.

- Development of a new planning system with real-time information on each order, that is information about changes of plans, lack of authorisation, lack of materials, lack of capacity and customer specifications. The purpose of this work was to improve prioritisation of orders and to supervise consequences of plan changes.

5 Discussion

The tasks of order management will change radically in future. In brief, mass customisation will give way to customer-driven manufacturing. The goal will be to maintain satisfactory utilisation of resources and an acceptable profit with an increased adaptation to customer-specific orders and a short and precise time of delivery. This anticipated strategic oriented change in work pattern will have a significant impact of staffing issues. These trends will mean that the employees of the future will need to possess various types of skills and qualifications.

A similar development has taken place in production where self-managed work teams comply with the new conditions [16]. This change calls for retraining of employees, and a corresponding re-education will be necessary for employees in the administration of these new manufacturing techniques. A co-operation between production groups and administrative groups, perhaps best achieved by organisational structure changes, will hopefully contribute to an improved control in future.

A feature of the trends in Danish manufacturing over the last three decades has been improvements in production techniques, production facilities and the introduction of improved business processes. Associated with this trend has been a move towards order-specific customisation which has meant the adoption of streamlined business processes. In this paper, researchers used data gained from two Danish manufacturing companies that were used as case studies to provide data. Two major elements of improvement that were found were the coordination of activities in the order process, and, the associated analysis of the information flow in the case companies.

6 Conclusion

As production processes have changed so too have the demands placed on the production designers and schedulers, especially with frequent customer requests. Many of the information systems in use were not connected to each other leading to errors and subsequent rework. These new trends put pressures on the current organisational design attributes. The researchers also found that a number of activities were adding value to the processes but the customer was not willing to pay for them. Additionally there had been examples of creeping form filling. The researchers predict that order management will change dramatically in the future; giving rise to different organisational models, and, that supervisors and employees will have the need for additional training for the increased skill levels demanded.

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Multidisciplinary Product Decomposition and Analysis Based on Design Structure Matrix Modeling

Tufail Habib

Abstract Design structure matrix (DSM) modeling in complex system design supports to define physical and logical configuration of subsystems, components, and their relationships. This modeling includes product decomposition, identification of interfaces, and structure analysis to increase the architectural understanding of the system. Since product architecture has broad implications in relation to product life cycle issues, in this paper, mechatronic product is decomposed into subsystems and components, and then, DSM model is developed to examine the extent of modularity in the system and to manage multiple interactions across subsystems and components. For this purpose, Cambridge advanced modeler (CAM) software tool is used to develop the system matrix. The analysis of the product (printer) architecture includes clustering, partitioning as well as structure analysis of the system. The DSM analysis is helpful to support decisions about product redesign and modularization.

Keywords Design structure matrix · Complexity · Interfaces · Mechatronic products

1 Introduction

Mechatronic products such as hybrid vehicles, industrial robots, medical instruments, and printers have been developed through the functional and spatial integration of subsystems with various engineering disciplines to fulfill the market needs. For this purpose, various approaches, models, and analysis tools are used to represent and understand the architecture of complex mechatronic systems. Since,

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the decisions about product architecture are relevant to the overall function of the product, which has broad implications related to product performance, product change, product variety, component standardization, and manufacturability [1].

According to Ulrich and Eppinger, "The architecture of a product is the scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact" [2]. Product architecture is thought about in terms of its modules and decomposing a system into independent parts or modules that can be treated as logical units [3]. It is the process of rearranging known parts into new architectures, and it revolves around redesigning the interfaces of key components to make them more modular in order to achieve a higher level of system performance in one or various dimensions [4], which is also relevant to mass customization (MC) in products. The aim of developing and using modules in product architecture is partly to make it possible to create customized products for the market and partly to reduce the number of variants which have to be dealt with internally in the company and thus to reduce complexity and cost [5].

Complexity is involved in the design and development of mechatronic systems due to number of subsystems, components and their interactions, and other aspects. According to Weber, complexity is an attribute of a system and can be divided into various aspects such as numerical, relational, variational, disciplinary, and organization complexity [6]. These aspects can be the number of subsystems, components and their relations, and variants as important characteristics of complexity. The degree of complexity is also relevant to the number of disciplines and the distribution of work [7]. In the context of mechatronic systems, designers and engineers need to deal with various aspects of complexity. Market requirements are also attributed to complexity due to customization that requires number of variants in products. Interaction of disciplines and distribution of work is also an issue especially for multidisciplinary products. In order to address these issues, various approaches and analysis tools are used; one of such tools is design structure matrix (DSM) to model complex products.

The DSM is a network modeling tool to represent the components of a system and their interactions, therefore, highlighting the systems architecture [8]. DSM first introduced by Steward [9] followed by many authors in different fields with a range of applications to product and organization domains. Various organizations and industry such as BMW, Audi, Hilti, NASA, Boeing, General motors, Intel, Kodak, Mozilla, Timken and BP etc., used it for various issues relevant to product, organizational, and process architecture modeling. In the domain of product development, the component-based DSM could be combined with the task and team DSMs to include the modularization in the rest of the design process planning using multi-domain DSM [10]. The method leaves more business-oriented factors and product functionality up to the designer's judgment after, first, simplifying the architecture by decomposition and interface management. Therefore, it is important to raise the following research question:

How the functional elements in a product can be decomposed into components by identifying their interrelationships to assess the degree of modularity as there is

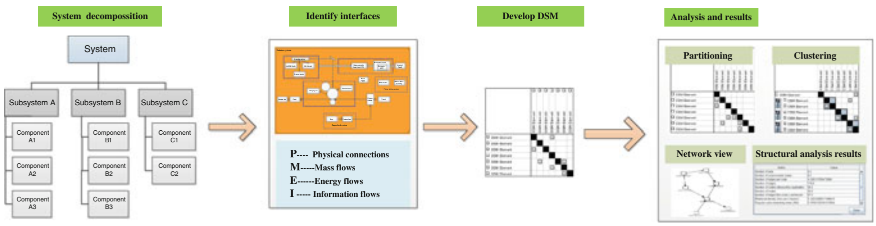

Fig. 1 Overall approach for product decomposition and analysis using DSM modeling (adapted from Eppinger and Browning [8])

always a trade-off between modules and market requirements on one hand, and functionality and performance on the other in mechatronic products/systems?

The complexity in multi-domain products requires decomposing them into subsystem and components, to guide the design requirements and to identify the solution space for functional improvements. This work implement component-based DSM (using printer as an example) in order to address the issue of system decomposition and interface management. The outcome of this paper is product decomposition to increase the architectural understanding of the multi-domain system, to examine the degree of modularity in the system, and to manage interactions across subsystems and components.

2 Methodology

In this methodology through system decomposition, complex products can be decomposed into subsystems, components, and functions. A modeling tool such as DSM is used in a software tool to represent the system elements and their interactions in order to generate the system architecture. In this example, the architecture is used to identify modules in the system, manage interactions across subsystems and components, and structure analysis results are presented.

Figure 1 represents an overall approach in this paper that is based on [8]. After system decomposition, the relationships between system components are identified. For the printer case, data about interfaces and physical structure are collected from product manuals, product videos, and physical observation of the product. In the next step, all the elements of the system are placed along rows and columns in a matrix display format. For this purpose, Cambridge advanced modeler (CAM) software tool [11] is used to develop the system matrix. Finally, the analysis of the system architecture (DSM form) is performed (e.g., clustering, partitioning, and displaying the elements in a network diagram). This DSM can be further extended to multiple domain matrices (MDM) for analyzing issues related to process and organization; however, this paper is limited to product architecture DSM.

3 System Decomposition and Identification of Interfaces

3.1 System Decomposition

In general, main subsystems of the printers are image-formation system, paper feed and delivery system, scanning system, formatter and control system, and fuser system. In the printer example, other functional elements such as duplexing unit and envelops' feeder systems are considered as optional systems to simplify the DSM model.

3.2 Identify Interfaces between System Components

The following types of interfaces are identified in the printer system:

- Physical connections
- Material (e.g., toner, paper)
- Energy flows (e.g., mechanical rotary, electrical, thermal, chemical, etc.)
- Information flows (e.g., image data, sensor signals, and actuator commands).

Spatial interfaces indicate that physical adjacency is needed for alignment, orientation, serviceability, assembly, and weight. For example, scanning mirror and focusing lens are in physical contact with scanning motor, when scanning mirror is rotated by motor, LASER beam reflects off the mirror, through a set of focusing lenses that is directed on photosensitive drum. A spatial connection between scanning motor and mirror is established in order to reflect beam on photosensitive drum. The alignment and orientation of the drum and charging roller are the necessary features to create a uniform negative potential on the drum surface that is necessary for the image development and its subsequent transfer to paper. Thus, a physical interface between charging roller and photosensitive drum is identified.

During the fusing process, the toner is fused into the paper by heat and pressure to produce a permanent image. The paper passes between a heated fusing roller and a pressure roller. This melts the toner and presses it into the paper. The quality of the fusing process depends on heat and pressure produced by fusing roller and pressure roller and their interaction with paper. Thus, a spatial interface is created between paper and fusing roller as well as paper and pressure roller.

Material interfaces indicate a functional requirement related to transferring mass flows such as toner and paper. For example, the developing cylinder must be able to attract toner, and the toner must obtain negative surface charge as the developing cylinder is connected to power supply. Thus, developing cylinder depends on power supply to be able to attract toner, while the toner must be attracted by this process. This results in a symmetrical dependency.

Energy flow indicates a functional requirement related to transferring mechanical energy, heat energy, vibration energy, electrical energy, noise, etc.

Fig. 2 DSM showing four elements of a system and their relationships

	A	B	C	D
A			X	
B				X
C	X			
D		X	X	

In printer example, for instance, the variation in the print density depends on the DC bias given to the developing cylinder, which causes more or less toner to be attracted to the developing cylinder, hence developing cylinder and power supply is related by (electrical) energy. Similarly, motor and drive assemblies are related by power transmission due to mechanical energy. Heat transfer from heater to cooling fan is kind of (thermal) energy interface. Although energy interfaces such as chemical, vibrations are also present in this kind of systems, however, they are not considered in this example.

Information interface indicates a functional requirement related to transferring sensor signals or controls, image data, and actuator commands. For instance, information about LASER beam is send to central processing unit (CPU) by the beam detect (BD) sensor; these two are related by information interface. Similarly, information about image formation is transferred from control panel to formatter CPU and is highlighted by information relation. When the power switch of the printer is turned on and the printer enters in the standby mode, the CPU outputs the signals to drive the loads such as laser diode, motors, and solenoids, based on the print commands and the image data input from the external device. CPU and the loads are connected by information (image data and actuator commands) dependency.

3.3 Develop Design Structure Matrix

The tool that is used to handle relations between items is widely known as the DSM. As shown in Fig. 2, a square matrix represents the elements in a system (the shaded cells along the diagonal) and their interactions (the off-diagonal marks). There are two possibilities to read the matrix. One can read across an element's row to see its inputs and down its columns to see its outputs although the opposite convention, the transpose of the matrix, is also used. For instance, element D receives inputs from elements B and C and providing an output to element B, as shown in Fig. 2.

To model product architecture, the DSM elements are product components and their interactions are the interfaces between the components. In structure analysis, DSM elements are called as nodes and their interactions as edges of a system.

3.3.1 DSM Model

The composite DSM (comprising multiple interfaces) model using CAM is displayed in Fig. 3 that shows the decomposition of the printer system into eight subsystems and 38 functional components. Four types of interfaces such as P-M-E-I (physical, material, energy, and information) are indicated in the DSM. Eight subsystems and two optional systems are discussed in Sect. 3.1.

4 Results and Analysis

Once the DSM model is developed, the analysis of the system can be performed with the following types:

- Clustering
- Partitioning
- Structure analysis.

Initially, a DSM based only on physical interfaces is analyzed by applying clustering algorithm using CAM. The results, as illustrated in Fig. 4, identify seven of the subsystems as somehow modular, as having more interfaces among components in each subsystem. These modular subsystems are scanning system, paper feed system, tray assembly, LASER and BD system, and paper delivery and fuser systems. As only physical connections are used, there are no interfaces with elements such as image formation and control software, and they are placed independently in the model. The DSM also shows the remaining subsystems as more spatially distributed. For instance, printer control system and printer drive assembly are more functionally distributed across the printer system, or in other words, their structure is more integrative than modular one.

To analyze composite DSM, partitioning algorithm is applied to it. The CAM tool uses loop-searching algorithm, which basically tries to accumulate dependencies on one side of the matrix diagonal. If this alignment cannot be realized completely, the partitioning tries to arrange dependencies as close as possible to the diagonal. Partitioning is also used to minimize the size of the feedback loops (A feedback loop consists of two or more nodes of a DSM, which are interlocked sequentially by edges and reciprocally influence each other [7]). Complex structures possess feedback loops that do not allow an alignment of edges at one side of the matrix diagonal. Partitioning then tries to align a minimum of edges below and all edges as close as possible to the diagonal.

In general, partitioning can provide information about the existence of feedback loops and can determine the strongly connected parts implied in a structure. Groups of nodes can also be identified that are suitable for modular design. However, it is not able to provide information about feedback loops in specific nodes. In Fig. 5, interfaces of the main controller, power supply, and printer drive

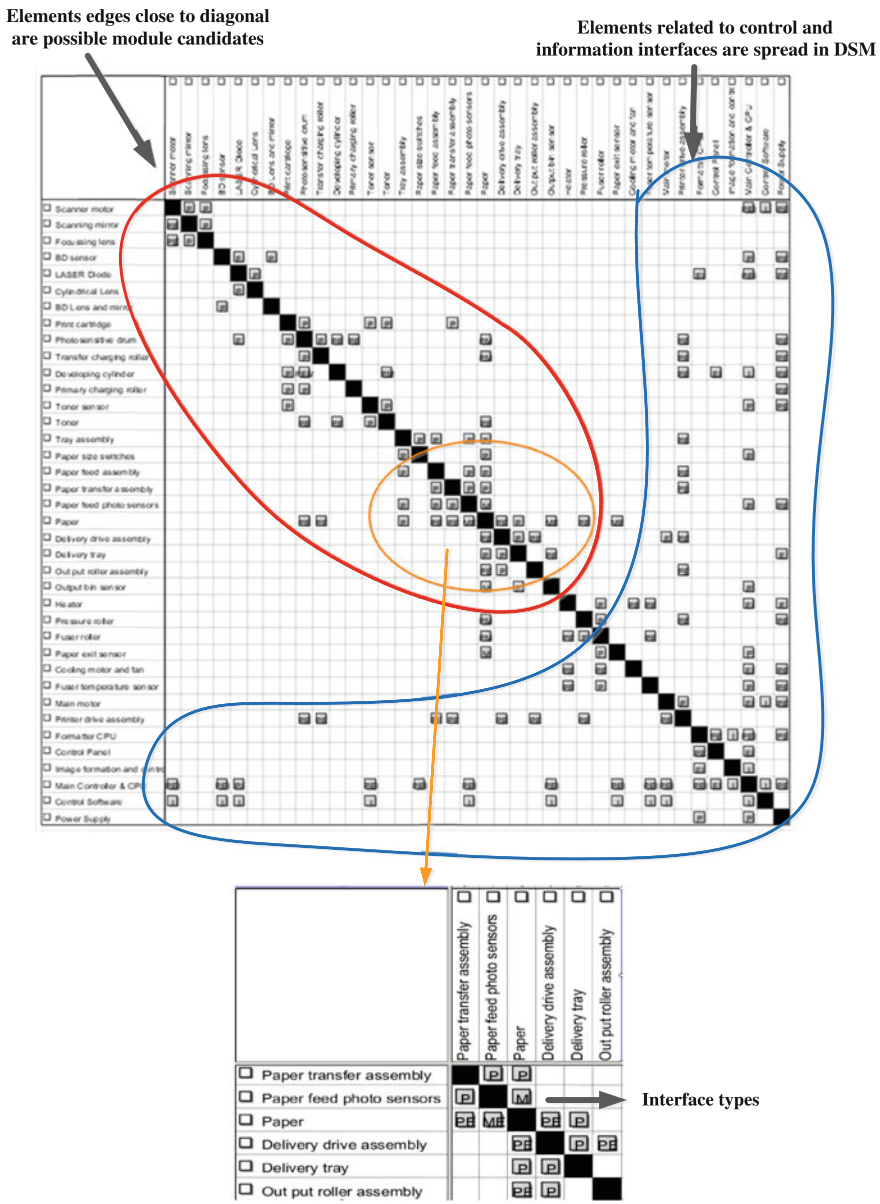

Fig. 3 Printer system (architecture DSM) components and their relationships

assembly are sparser than the other elements. The remaining elements are relatively close to the diagonal that can be considered as possible module candidates. The reason for not accumulating near the diagonal is due to many interfaces shared by some of the elements in a system.

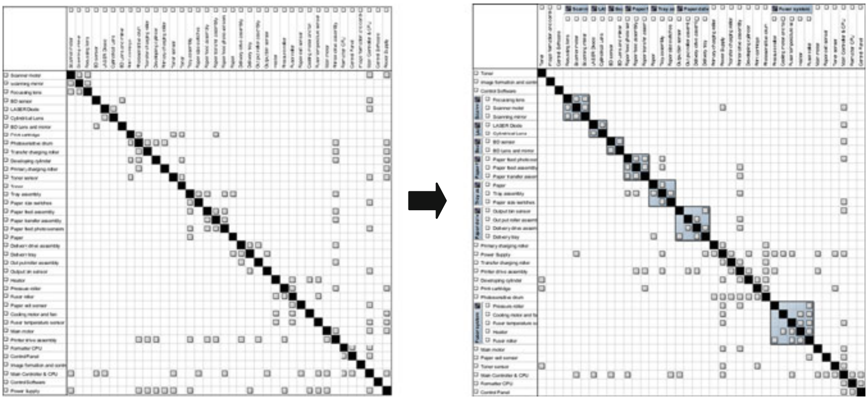

Fig. 4 DSM of physical connections and its modular structure after applying clustering algorithm

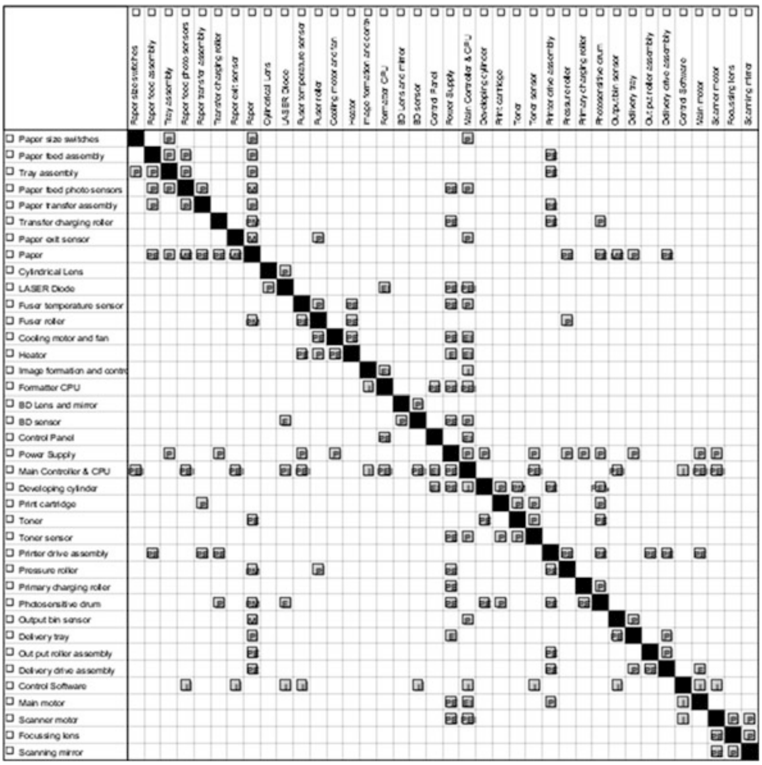

Fig. 5 Partitioning of composite DSM

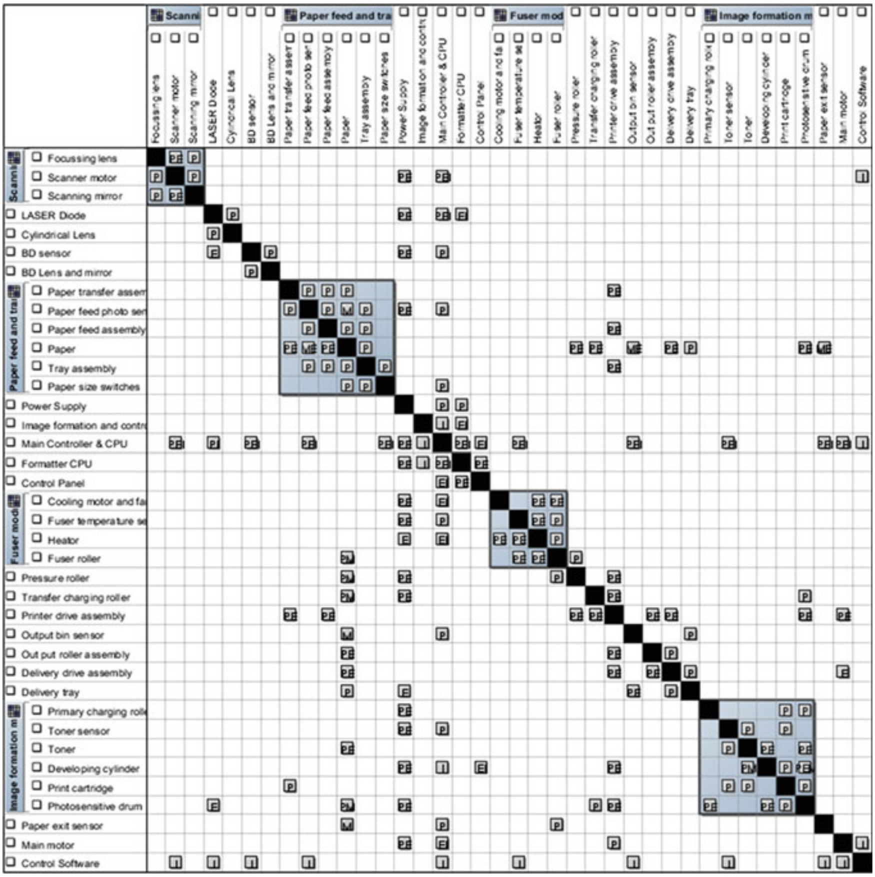

Fig. 6 Clustering of composite DSM

The designer can draw useful insights from the DSM architecture after clustering the elements in composite DSM. In Fig 6, the DSM model identified four of the subsystems as somehow modular, as more interfaces among components in each subsystem. These modular subsystems are scanning system, paper feed system, and paper delivery and fuser systems. The DSM also shows the remaining subsystems as more distributed. These systems are printer control system, main motor, and printer drive assembly that are more functionally distributed across the printer system, or in other words, their structure is more integrative than modular one.

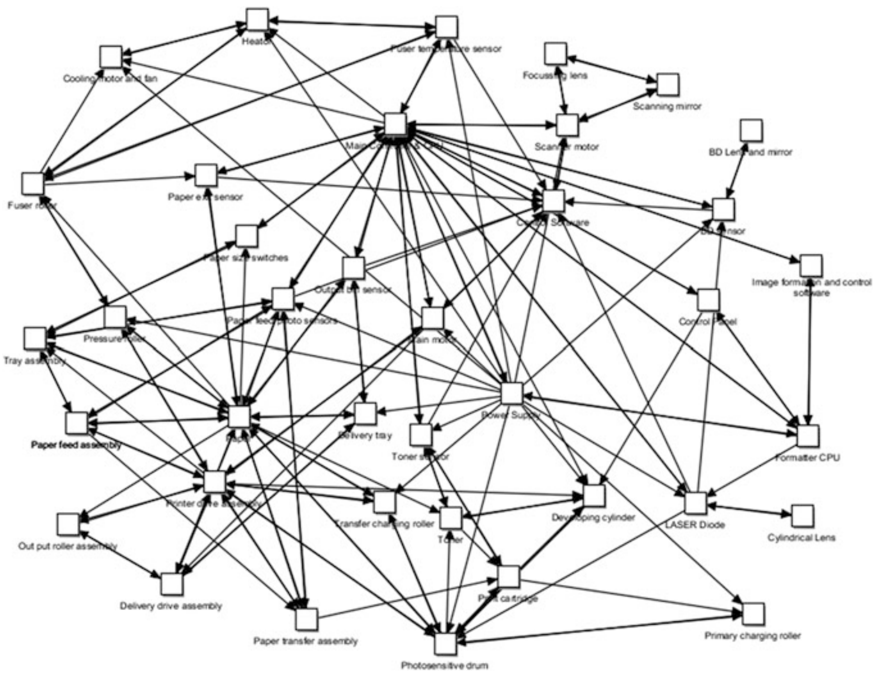

Fig. 7 Structure representation in network view

4.1 Structure Representation and Analysis

The network view is used to visualize the dependency information in the detailed printer system; each line represents a connection in the DSM, from this diagram elements with more integrated connections can be visualized, though it is hard to read especially when there are many components and interfaces. In the network view as shown in Fig. 7, power supply, main controller, and printer drive assembly are more connected than other elements.

From the network view, each node represents the components and assemblies in the printer architecture; on average, more than one interface is present with each component; it also points toward the functions performed by each component in the architecture as is distributed. According to Ulrich’s definition of modular architecture having one-to-one mapping between functions and components, modular structures must have a smaller function-to-component ratio than integral products. Though the function-to-component ratio is not calculated in this case, but the distribution of the interfaces is much higher, that must be reduced to increase the degree of modularity in the architecture.

The attainability in a structure is measured to assess the change in any node and its impact on other nodes in the structure. Attainability of a node is the ratio of the number of nodes it reaches to the maximum number of nodes it could reach

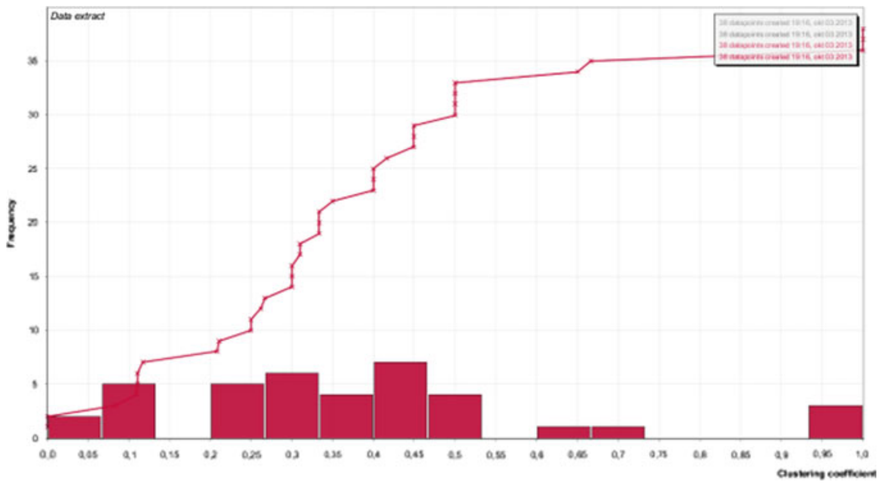

Fig. 8 The level of connectivity in the elements of composite DSM

theoretically. In the proposed example, the attainability in the nodes such as CPU control, printer drive assembly, power supply is relatively more than the remaining nodes of the system. A high valve of attainability means that many other nodes can be affected by any change in the node that is considered for any change. In general, the attainability in the nodes must be reduced in order to be able to make structural changes or redesign the architecture, though other criteria such as paths and lengths of the nodes are also relevant for proper characterization of the nodes.

Clustering is a measure, or a heuristic, to define the level of connectivity between a group of people or components. The clustering coefficient (CC) is the measure of this level of connectivity [12]. In the printer example, scanning mirror is having two edges and both are closely connected; hence, its CC is equal to 1. While cylindrical lens is having one edge and no other connections, therefore, its CC is 0. In Fig. 8, CC for most of the nodes is close to center that point's medium level of connectivity in nodes.

Table 1 represents the total number of clusters formed, number of nodes, edges and their connections, nonzero fraction (NZF) as well as singular value modularity index (SMI) in the structure. There are in total four clusters, all the nodes are connected with some kind of interface. The SMI and NZF are introduced by Refs. [10, 13], where NZF, is the fraction of nonzero entries without diagonal values, that can be computed as,

$$\text{Non zero fraction} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\text{DSM}_{ij}}{N(N-1)} \tag{1}$$

where, N = number of components.

According to the NZF, the density of the system is 0.122 or 12 %. In other words, only 172 of the 1,406 off-diagonal cells are occupied in the system. While

Table 1 Structure analysis results of composite DSM

Structural analysis results

Metric	Value
Number of sets	4.0
Number of unconnected nodes	0.0
Number of edges per node	4.526315789473684
Number of edges	172.0
Number of nodes (discounting duplicates)	38.0
Number of nodes	38.0
Number of edges that cross a set border	60.0
Relational density (Non-zero fraction)	0.1223328591749644З
Singular-value modularity index (SMI)	0.2556315789473684З

complex, with as many as 38 elements and lot of interrelationships, the density is only 12 %.

The *SMI* evaluates the overall connection scheme between the components; however, this index does not evaluate that how components are grouped into modules. The SMI measures the decay rate of the singular values in the system [13],

$$\mathrm{SMI} = \frac{1}{N} \arg\ \min\alpha \sum_{i=1}^{N} \left| \frac{\sigma_i}{\sigma_1} - e^{-[i-1]/\alpha} \right| \quad (2)$$

where, σ is the singular values in the matrix, and N is the number of components, and α determines the decay rate. This index is theoretically bounded and based on numbers between 0 and 1. According to [10], an SMI closer to 1.0 indicates a higher degree of modularity, where the connectivity information is more distributed. An SMI closer to zero indicates a more integral system. The SMI, in printer case is closer to zero, that indicates an integral system, even though the algorithm formed some modules. One reason can be the number of edges formed by interfaces related to elements such as power supply, paper, main controller CPU, as these interfaces are more distributed in DSM.

5 Discussion and Conclusions

This paper is about a case study analyzing an existing product by applying the component DSM method. The results are not generalizable and primarily dependent on product type. One reason that determines the degree of modularization in a product is dependent on the number of interactions, component connectivity, and how spread these interactions are in the matrix.

In this work, decomposition of the mechatronic product is performed to analyze the architecture of the multi-domain system. For this purpose, DSM approach is used by decomposing the system into subsystems and components and, in the process, establishes the component interfaces. After applying the clustering algorithm, the DSM formed by only physical interfaces is different than the composite DSM. In case of physical interface DSM, the number of interfaces is significantly less and not spread like composite DSM; hence, more modules are formed by clustering algorithm. In composite DSM, more interfaces are there, as elements related to information and control are more spread and linked to other elements in the structure as compared to those related to mechanical elements. The matrix formed by partitioning highlights important aspect related to identification of modules. As partitioning, regroup most of the elements close to the diagonal that can be considered as possible module candidates. Some interfaces are not accumulating near the diagonal is due to many interfaces shared by some of the elements in a system.

Structural analysis of the system architecture is an important aspect that represents nodes, edges, interfaces, and modules. A high degree of connectivity in a structure can make the system analysis difficult. The quantity of feedback loops may increase drastically as connectivity of elements in a structure becomes higher. This indicates integral products' architectures and results in more connected product that require more efforts to redesign. From the SMI index and Ulrich's definition of product architecture, the printer architecture is close to integrative, though some modules are formed after clustering. Structural optimization is useful when a fundamental system structure has to be redesigned in order to form product platforms to create variety. This supports developers in the creation of specific system variants for product customization [7]. This implies that through structure optimization using DSM methods, a product platform can be developed from a single product that can be used for customization in the product. Structure optimization involves application of various approaches such as tearing and structure Pareto analysis.

The development of product architecture based on design parameters and their interfaces is a useful approach for product upgrading and MC. For instance, for better performance, increasing the copying speed of the printer can be achieved by changing design parameters such as speed of a motor or its size. Once the modular structure is in place along with relevant interfaces, the designer can decide either to replace the component (with a high speed motor) or to use a controllable component (variable resistance in this case), that also involve change in the control software, in case of mechatronic products. This upgrading may not change to a large extent the physical configuration of the system. As shown in the printer example, though main motor is not placed in any module, any change may influence the interfaces with subsystems and components such as printer drive assembly, main CPU, and control software. Furthermore, the design parameters can be changed to create variety in the product, such as changing speed and size of the motor. This must have an effect on the overall performance of the product.

One issue related to the design of complex systems is the trade-off between modularity and integrality. What should be the degree of modularity in case of computer-controlled mechatronic products? According to Hollta and Whitney [10, 14], integral architecture is driven by product performance (i.e., power consumption, weight, size, speed, etc.) and cost while modular architecture by business demands such as variety, product change, engineering standards, and service requirements. They argue that how total modularity is not always desirable in case of high-power mechanical products as opposed to low power signal processor type products. That argument is supported by some high-performance systems such as automotive and aerospace vehicles appear to favor highly coupled architectures, where one part fulfills potentially many functions [15]. It means that products with technical performance constraints (e.g., light weight, tight packaging, power efficiency, speed) tend to have a larger function-to-component ratio, i.e., they are more integral such as electronic calculator and mobile phones (excluding batteries and cover). But on the other hand, products like computers are highly modular as compared to products that contain computer control mechanical parts such as printers, car engines even though they are microprocessor-based products (or subproducts).

The optimal solution in case of mechatronic systems could be a high-performance product, with a few modules that can be used for commonality and flexible design for customization. However, that statement cannot be generalized due to various factors and requirements. Though mechatronics is a design process to develop high-performance products by the functional and spatial integration of subsystems with various engineering disciplines, more software and electronics are integrated to mechanical products for improved performance. Apart from these functional improvements, there must be some compromise on performance to satisfy market needs. Therefore, the *degree of modularity* in mechatronic products varies and cannot be generalized due to performance requirements, product structure, market demands, etc.

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Open Innovation, Co-Creation and Mass Customisation: What Role for 3D Printing Platforms?

Thierry Rayna, Ludmila Striukova and John Darlington

Abstract Both open innovation and 3D printing technologies have attracted a lot of attention recently. Our main aim is to investigate the role of online 3D printing platforms in open innovation with customers. There are four main contributions in this paper. Firstly, it offers a better understanding of the relationship between open innovation, co-creation and mass customisation and indicates in which case they overlap. Secondly, it provides an 'inside–outside' typology of co-creation that enables to classify co-creation activities according to their aim and type of collaboration. The third main contribution is a typology of online 3D printing platforms, based on their core services. Finally, by combining the two typologies, we are able to demonstrate the role played by each platform based on type of co-creation activity considered.

Keywords 3D Printing · Crowdsourcing · Open innovation · Mass customisation · Co-creation · Online platforms

1 Introduction

Ever since Chesbrough coined the term 'Open Innovation' in his seminal 2003 work [1], there has been a growing interest from both academics and practitioners in this concept. This idea that innovation does not solely take place inside the firm

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has now become very popular and firms, small or large, have been trying to integrate this new way of innovating in their strategies. However, focus has generally been put either on open innovation with other firms or open innovation with the academic world. Yet customers can also be an essential source of ideas and engaging customers in co-creation activities (designing a new product or improving an existing one) can provide firms with a strong competitive advantage.

Indeed, many firms have been using ideas and feedback from consumers to innovate and neither open innovation nor co-creation with customers is new phenomena. Yet, until recently, these practices were limited in extent and restricted to very particular situations. Standardisation and specialisation were governing innovation practices, and although consumer input was sometimes used, it was mostly used to 'guess' the needs of the majority of consumers.

The recent progresses of ICTs have changed the situation considerably. In particular, the advent of Web 2.0 technologies and social media has enabled firms to permanently engage in co-creation activities with a large number of customers. Furthermore, beforehand, the 'outside–in' aspect of open innovation with customers was far more exploited than the 'inside–out' aspect. Indeed, without adequate means of productions widely available to customers, it was difficult for them to use and develop ideas of the firms that were so far unexploited. Recent progress in ICTs has changed that and enabled customers to actually engage in developing ideas put forward by the firms and transform these ideas into innovative products. Until recently, however, this ability has been mainly restricted to the digital goods. However, the recent advances in 3D printing technologies have the potential to extend the opportunities of co-creation with customers to the realm of physical objects.

Although prices of 3D printers have considerably decreased over the past few years, advanced printers remain rather expensive. On the lower end of the range, printers can be found for less than $1,000, but the relatively low quality of the objects they produce restrict them to rapid prototyping activities. Aiming to bridge this gap, several online 3D printing platforms have appeared over the past few years. The first of such platforms, Ponoko, appeared in 2007 and there are now 14 online platforms that enable firms and customers to engage in co-creation activities related to 3D objects. Interestingly, these platforms are rather heterogeneous and do not systematically offer the same services, which implies that they aim to satisfy different needs.

The main goal of this paper is to investigate the role that these online 3D printing platforms play in open innovation activities conducted with customers. Since these technologies, as well as the related IT systems, are in their early stage of development, our methodology is both descriptive and prescriptive.

The paper has the following structure. In the first section, we focus on open innovation with customers and on the role played by co-creation and mass customisation in this form of innovation. In the second section, we detail the different forms of co-creation and provide a typology enabling to classify co-creation activities. In section three, we present in detail the current online 3D printing platforms and provide a typology of such platform, which is based on the core services these platforms deliver. The last section combines the two typologies to investigate the types of co-creation activities that each platform enables.

2 Open Innovation with Customers

The importance of external sources of innovation started to be emphasised by researchers back in the 1980s [2] and gained even more attention since 2003, when Chesbrough coined the term ‘open innovation’.

Open innovation can typically take three forms [3]. The first form, also known as inbound open innovation [4], is ‘outside–in’ and consists in integrating suppliers and customers as external source of knowledge. The second form, ‘inside–out’, or outbound open innovation [4] aims to increase profits by bringing ideas to the outside environment, so that ‘outsiders’ can develop ideas and technologies that are not used by the firm. The last form is a combination of both forms and is referred to as coupled open innovation.

Until recently, open innovation with customers was mainly ‘inside–out’. Companies were using customers as a source of ideas for new products or improvements of existing products [2, 5]. Lately, however, there has been a shift from simply exploiting customer knowledge to co-creating knowledge with customers [6]. Nowadays, open innovation with customers has even taken the form of a coupled process focused on co-creation. Customers are involved in generating ideas for new products, co-creating products with firms, testing finished products and in providing end user product support [7]. Furthermore, consumers are no longer simply external sources of ideas (outside–in), but can also become external paths to market (inside–out) [8, 9].

Co-creation is an active, creative and social collaborative process between producers and users that aims to create value for customers [10]. There are two different forms of co-creation. Autonomous co-creation relates to co-creation activities led by customers that take place independently from companies [11]. Although customers may still be using tools and platforms originally provided by firms, they do so on their own free will, without any incentive provided by the companies. In contrast, sponsored co-creation relates to co-creation activities conducted by individuals customers or by customers communities that take place at the initiative of a company or any other established organisation.

Co-creation can occur at different stages of the production process: during the product design stage (co-design), the product manufacturing stage (co-manufacturing) and even during the product distribution stage. In addition to taking place between companies and customers, co-creation can also take place between individual customers. These co-creation communities are also known as ‘communities of creation’ [6] or ‘communities of co-design’ [12].

Co-creation corresponds to the customer-related part of open innovation: ‘open innovating’ with customers necessarily implies engaging in co-creation with them.

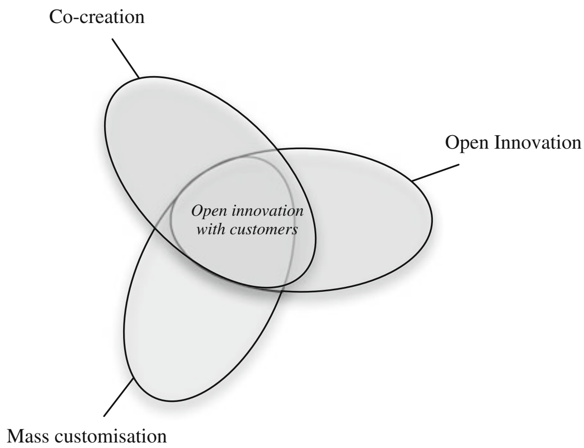

Fig. 1 Relationship between open innovation, co-creation and mass customisation

However, although co-creation is a necessary condition of open innovation with customers, it is not always a sufficient condition. Indeed, not all co-creation activities carried out with customers lead to open innovation, as innovation requires successful commercialisation. Hence, suggestions submitted by customers that are not acted upon, or a collaborative design that does not go beyond the prototype stage, are examples of co-creation activities that do not result in innovation.

Yet the recent raise of mass customisation has strengthened the link between co-creation and innovation. Indeed, when the target of co-creation is the mass market, it is likely that few co-creation activities with customers will lead to a commercially successful product and, hence, to an innovation. However, if co-creation takes place within the context of mass customisation, the situation is radically different since customers engaged in it are no longer trying to guess what the mass market want, but instead help develop a product that fulfils their needs. For this reason, most mass customisation co-creation activities are likely to result in commercialisation of the product (and hence in innovation). The key difference is, of course, that this takes place in a 'market of one' instead of the mass market.

Mass customisation relates to the production of personalised or custom/tailored goods or services on a large scale (i.e. customisation is the rule and not the exception). Although, co-creation activities increasingly result in mass-customised products, mass customisation does not necessarily involve co-creation activities [13] or even lead to open innovation [14, 15]. For instance, when mass customisation implies choosing from a set of predetermined options (e.g. colour, size, add-ons), this is not co-creation, as customers do not provide actual input, besides choosing amongst options that were set by the firm (possibly without any customer input). Furthermore, selecting from predetermined options does not lead to innovation, as this does not provide any element of novelty [15]. Figure 1 summarises the relationship between open innovation, co-creation and mass customisation.

Table 1 ‘Inside–outside’ categorisation of co-creation activities

	Mass production	Mass customisation
Differentiated	Crowdsourcing Social media	Customised objects Crowd customisation
Integrated	Open innovation platforms Open source	Co-design platforms

3 Categorising Co-Creation Activities

Co-creation activities may take different forms. To categorise the different co-creation activities, we consider two critical aspects: whether the roles of the consumers and firms are differentiated or integrated (‘inside’) and whether the resulting product is aimed at the mass market or is customised (‘outside’). This ‘inside–outside’ approach enables us to cover both inside–out and outside–in aspects of open innovation [3].

The first aspect of this classification relates to the complementarity of the activities of consumers and firms in the co-creation process. For instance, the consumer might design the product and the firm manufacture it. In the case of DIY furniture, the firms supply flat-packed furniture and consumers assemble the object themselves. In contrast, other co-creation activities involve firms and consumers working together on the same aspect of the production process, for instance, when a customer is ordering a custom made piece of jewellery or when firms and customers work together writing a computer program.

The second aspect relates to whether the output of the co-creation activity is meant to be mass-produced or is tailored for a specific consumer. This aspect is particularly important as it relates to the value created and incentives to participate in the co-creation activity. Some co-creation activities result in a product ‘valuable to one’ (mass customisation), while others lead to products that are ‘valuable to the many’ (mass production).

Table 1 presents our classification of co-creation, as well as examples for each type of co-creation. Nowadays, the most common type of co-creation activity is ‘differentiated/mass production’. Indeed, most crowdsourcing activities belong to this type of co-creation, as crowdsourcing typically implies that the ‘crowd’ is in charge of one type of activity (usually design), while the company takes care of the rest and mass-manufactures the product.

4 Typology of Online 3D Printing Platforms

Our research enabled us to identify 14 online platforms related to 3D printing and opened to consumers. Aside these platforms, there are several 3D platforms offering B2B and B2C solutions to businesses (e.g. Digital Forming). Since they are not (directly) opened to consumers, these platforms were not considered.

Table 2 Main services (design and manufacturing) offered by 3D platforms

Service	Description
Design supply	Supply of 3D models (for free or for a fee)
Design hosting	Hosting of third-party designs, which are then sold (marketplace) or offered free-of-charge (repository)
Design customisation	Hosted designs can be customised by consumers.
Design co-creation	Help users designing a 3D object, generally by transforming 2D sketches or pictures into a 3D object
Design crowdsourcing	Users crowdsource a design by posting a project that is then developed further by the crowd
Printing	Printing of 3D models shipped or delivered in store
Printer sales	Supply 3D printers (in store or through mail order) to customers, who are then able to print 3D objects
Printing crowdsourcing	Intermediary service between users wanting to print 3D objects and owners of 3D printers

Amongst these 14 platforms, five originate from the USA (3DLT, Cubify Cloud, Krafwürx, MakerBot/Thingiverse, MakeXYZ), three from the UK (3D CreationLab, 3DPrintUK, iMakr), one from Australia (Additer), one from New Zealand (Ponoko) and four from the continental Europe: 3D Burrito (Sweden), i.Materialise (Belgium), Sculpteo (France) and Shapeways (Netherlands). Furthermore, three of these companies (Ponoko, Sculpteo, Shapeways), although not originally located in the USA, have opened offices there. Finally, it is to be noted that two of the companies studied have a physical store: Thingiverse/Markerbot in New York, USA and iMakr in London, UK.

The first mover, Ponoko, launched its service back in 2007. A few other companies followed in the next two years (six platforms were launched between 2007 and 2009), but platform was launched in 2010 (probably because of the lack of maturity and adoption of the technology at the time). Starting in 2011, the growth resumed, with eight platforms launched between 2011 and 2013, and half of these platforms launched in the first 6 months of 2013.

At the moment, there are only few consumers and SMEs who are equipped with a 3D printer, and those who do have a 3D printer usually can only print with plastic (and they might want or need objects made of other materials). Hence, these platforms have emerged to attempt to bridge this gap. Their customers are either people who want designs that they can print using their 3D printers or people who have designs, but do not own a printer (or, at least, not the one that prints with the material they want). There are also customers who want both to acquire designs and have them manufactured.

Because of these heterogeneous needs, there is room for specialisation in the market, which is reflected by the variety of combinations of services offered by 3D printing platforms. Some platforms only cover design aspects (3D Burrito, 3DLT) or manufacturing aspects (3DPrintUK, MakeXYZ). However, the majority of platforms (10 out of 14) cover both design and manufacturing aspects.

Table 3 Key services offered by each of the 3D printing platform

Company	Design			Manufacturing			Crowdsourcing platform
	Design market place	Design repository	Design service	Printing market place	Printing service	Printer sale	
Cubify Cloud	+				+	+	
i.Materialise	+		+		+		
Ponoko	+				+		
Sculpteo	+				+		
Shapeways	+		+		+		
3D Burrito	+						
3DLT	+						
3D CreationLab			+		+		
3DPrintUK					+		
iMakr			+		+	+	
Markerbot/ Thingiverse		+			+	+	
Additer							+
Kraftwürx							+
Makexyz				+			

Whether involved in design, manufacturing, or both, the main services offered by the existing online 3D printing platforms are rather similar. We identified eight different services, which are presented in Table 2. Five of these services (design supply, hosting, customisation, co-creation and crowdsourcing) relate to design aspects, while three of them (object printing, 3D printer sales, printing crowdsourcing) correspond to manufacturing.

Based on the core services offered, we were able to identify three broad categories of 3D printing platforms (Table 3). Out of the fourteen platforms, seven of them (Cubify Cloud, i.Materialise, Ponoko, Sculpteo, Shapeways, 3D Burrito, 3DLT) can be categorised as design marketplaces. Their main activity is to host and sell third-party designs of 3D objects. Three of these marketplaces (Cubify Cloud, i.Materialise, Sculpteo) also offer their own designs for sale ('Design supply'). The same three companies also offer users to customise these designs ('Design Customisation'). Sculpteo goes even further and enables users to customise third-party designs hosted on their platform. Two of the design marketplaces (i.Materialise and Shapeways) also offer co-creation design services to help third-parties turn their designs into a 3D object. However, none of the design marketplaces (currently) offers a design crowdsourcing service.

Once consumers purchase designs from these marketplaces, they are then able to print it at home using their own 3D printer or using five of these marketplaces (all except 3D Burrito and 3DLT). One of the marketplaces, Cubify Cloud, even sells 3D printers to consumers, so they are then able to print objects at home.

The second main category of platforms consists of companies that operate similarly to a traditional printing service (albeit a 3D one). The main objective of

3DCreationLab, 3DPrintUK, iMakr and Makerbot/Thingiverse is to enable users to 3D print their designs. Users upload their designs on these platforms' website and these designs are then 3D printed and shipped to the user. There are also physical stores (iMakr in London, Makerbot in New York), which offer to print objects from existing designs. In addition to its physical store, iMakr allows the online submission of designs. Both companies also sell home 3D printers.

Unlike design marketplaces, printing services generally do not supply or host designs (the only exception is Makerbot/Thingiverse, which operates a repository of free-of-charge designs supplied by users). However, two of these printing services (3DCreationLab and iMakr) also offer a co-creation design service to help users create 3D models of objects.

The last group in Table 3 consists of platforms that are neither design marketplaces nor printing services. One of them, MakeXYZ, is, so far, the only printing marketplace. It enables owners of 3D printers to supply their services and acts as an intermediary between them and people who require printing. In June 2013, MakeXYZ announced its partnership with 3DLT, one of the two design marketplaces without a printing service. The integration of these two services will, thus, result in another design marketplace with printing service (albeit a crowdsourced one).

The last two companies, Additer and Kraftwürx, are significantly different from other 3D printing services in this new market, which, otherwise, looks rather traditional (marketplaces, printing services, etc.). Indeed, they operate as full crowdsourcing platforms, which means that they enable users to crowdsource both design and manufacturing aspects.

For instance, there is a board on Kraftwürx's website, where users can post ideas and projects at any stage of development. Some of them post a very generic idea (for instance, showing different pieces of jewellery and asking the crowd to produce a personalised object 'in the spirit of' of the design of the objects posted). Others post 2D designs and need help turning them into 3D objects. Finally, other users already have a rough 3D model of the object and ask the crowd to help refine it, or make it functional.

Likewise, although some users seem to already have a precise idea of the material they would like to use, others expect the crowd to offer them different options. The crowd is also used to advise on can a variety of other manufacturing aspects (cost, proximity, quality, etc.).

To this respect, a rather surprising point in this study is that, aside from these two crowdsourcing platforms, none of the other twelve online 3D printing platforms use crowdsourcing or offer crowdsourcing services. However, this may be due to the fact that the technology is yet immature and that the tools to enable crowdsourcing are not yet available. Indeed, one of the essential aspects of crowdsourcing is the wide availability of tools (e.g. software, online platforms) that enable users to contribute to crowdsourcing at a very low cost and with minimal barriers to entry. At the moment, in many cases, advanced knowledge of highly technical 3D modelling software is often required to produce 3D objects. When intuitive and easy to use tools will be readily available, it might become more interesting for 3D platforms to include crowdsourcing as a part of their business model.

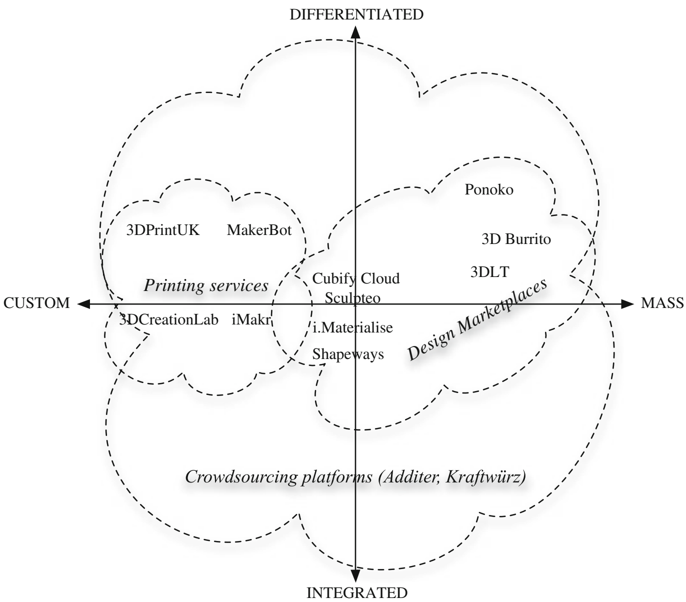

Fig. 2 Co-creation-based typology of 3D printing platforms

5 Types of Co-Creation and 3D Printing Platforms

In Sect. 3, we introduced a classification of co-creation activities. Using the typology presented in Table 1, it is possible to categorise the role that the fourteen online 3D platforms play with regard to co-creation (Fig. 2).

Printing services obviously belong to the 'differentiated/mass customisation' quadrant, as they relate to user manufacturing and lead to the creation of custom objects. By nature, the roles of firms and customers are differentiated, as customers provide the designs and these printing services transform designs into objects. However, as mentioned in Sect. 4, two of these platforms (3DCreationLab and iMakr) also offer a co-design service, so for these two platforms, there is an overlap with the 'integrated/mass customisation' quadrant.

The case of design marketplaces is slightly more complex. Indeed, as a few of these also offer a printing service, there are cases when no co-creation takes place. This is, for instance, the case when a customer purchases a 3D model through the marketplace and has it printed without customising it (beyond basic options).

In contrast, when a customer buys a 3D model on the marketplace and prints it at home, it is indeed a co-creation process with differentiated activities. However, whether this case belongs to mass production or mass customisation essentially depends on whether the object was customised or not. If it was not, then the co-creation activity can be considered as being a part of a mass production process. Indeed, although each customer 3D prints its own copy, it is the same identical object that is printed over and over again. It is, thus, actually a mass production process, albeit being a decentralised one.

However, some of the design marketplaces offer design customisation services. In such cases, the co-creation process relates to mass customisation. Also, depending on the type of design service offered (e.g. customisation, co-creation), the co-creation process becomes more or less integrated.

Finally, the case of crowdsourcing platforms is probably the most complex one, as depending on the type of activity that is crowdsourced and the extent of the crowdsourcing activity, the co-creation process can potentially fall in any of the categories. Indeed, some customers use Additer and Kraftwürx with the aim to mass-produce (again, not with the aim to produce millions of units, but in order to sell the same object to many customers). In that case, both design and manufacturing processes can include or exclude the co-creation activities.

The same is true for the co-creation activities that are related to mass customisation. However, these platforms give raise to a new form of co-creation activities: crowd customisation, which is a combination of crowdsourcing and mass customisation. In such a case, the 'wisdom of the crowd' is used not to satisfy the needs of the many (like it is for instance with threadless), but to satisfy the needs of one, in other words, the crowd is asked to help design and manufacture an object which has value for only one particular customer.

6 Conclusion

Co-creation with customers is a critical aspect of open innovation, but technological and cost constraints were, until recently, such that this form of innovation was only used in particular situations. By providing customers with easy to use and effective means of productions, recent technological progress has empowered consumers with the ability to create goods in the digital realm, thereby initiating their transformation from consumers to prosumers. 3D printing technologies have the potential to do the same in the world of physical object and, thereby, take co-creation to its full potential. However, for this to happen adequate co-creation platforms need to be built and this requires to fully understand the different aspects of co-creation.

In this paper, we examined the role of online 3D platforms in co-creation processes. To do so, we first investigated the relationship between open innovation, co-creation and mass customisation. We demonstrated that although there is a clear overlap between these three phenomena, they do not necessary imply one another. Yet, we have shown that the progresses made in manufacturing technologies have made it easier to combine them.

The second key contribution of this article is an 'inside–outside' typology of co-creation, which is based on both the means (complementarity of roles between firms and customers) and aims (mass market or individuals) of co-creation. This typology enables to understand better the challenges and opportunities related to co-creation.

Another key contribution is a typology of online 3D platforms, which is based on the core services we delivered. This typology enables us to identify three main categories of platforms: design marketplaces, printing services and crowdsourcing platforms. Finally, we have combined the two typologies in a mapping that enables to better understand which kind of platforms is suited for which kind of co-creation. This is critical to both online 3D platforms (in order to develop new services or fine-tune existing ones) and SMEs and consumers using these platforms.

An avenue for further research would be to use this mapping to critically assess the services provided by online 3D platforms and investigate how these services could be improved. It would also be interesting to see whether the two typologies enable to design types of platforms that do not yet exist. Finally, the typology of co-creation could be applied to other kinds of online platforms, such as Web 2.0 platforms.

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Open Innovation: Creating Value Through Co-Creation

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Abstract Research in the field of open innovation and creating value through co-creation are somehow new. The main objective of this study is to answer the question that "How open innovation helps companies in creating value through co-creation activities?" In order to do so, the authors conducted a qualitative research and finally found four main strategies that companies could follow in different situations. These strategies were: (1) Corrective product/service improvement, (2) incremental product/service improvement, (3) Crawling product/service improvement, and (4) Radical product/service improvement.

Keywords Co-creation · Open innovation · Value creation

1 Introduction

Nowadays, consumers have a more broad range of choices of products or/and services than they ever had before, but yet they seem unhappy. Firms invest in greater product/service diversity but are less able to differentiate themselves in the market [1]. For more than a hundred years, a company-oriented, view of value creation has shaped the industrial structure and the entire business environment, while this perspective often conflicts with what consumers' perception of value is [2].

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On the other hand, value creation is one of the main purposes and vital processes in economic transactions. Systems are value creation configurations of people, technologies, value propositions connecting internal and external service systems, and shared information [3]. Here, co-creation adds a new dynamics to the relationship between producer and customer through engaging customers directly in the production/distribution of value. In other words, customers can get involved at about any stage of the value chain [4]. In the existing literature on value creation and value co-creation, value is used as an abstract concept that seldom is specified in more concrete terms. In addition, one should note that value is a relationship between what one achieves and what one sacrifices [5].

While contributing substantial creative input/value, the co-creation activities also provide a variety business challenges by disrupting a closed business model of expertise, pushing toward an open innovation model [6]. Yet, some of the literature falls under the rubric of concepts such as "customization" and "co-production" for the use of a given customer/group of customers, some companies incorporate the ideas/designs suggested by consumers into their open innovation processes or specifically support co-creation activities [7].

In this paper, the authors review the existing literature on open innovation and co-creation, and then discuss the methodological issues. Then, the findings are discussed, and the paper concludes with four main strategies for creating value through open innovation activities. Finally, the limitations and future directions are elaborated and the paper concludes.

2 Literature Review

2.1 Open Innovation

Open innovation has become one of the important topics in the innovation management field. After Chesbrough's groundbreaking works in the last decade (see [8, 9]), it quickly became clear that the roots of open innovation go far back in history, and not just in the last few years. In an extensive literature review, after reviewing a hundred and fifty open innovation papers, Dahlander and Gann [10] found many references to concepts such as complementary assets, absorptive capacity, and the exploration versus exploitation discussion, which are different concepts with roots in open innovation phenomenon [11].

In today's information-based atmosphere, firms can no longer afford to rely completely on their own ideas in order to succeed in their business. Moreover, they cannot restrict their innovations to a single direction in the market [8]. Open innovation describes an emergent model of innovation in which firms draw on research and development (R&D) that may lie outside their own boundaries [12]. The open innovation paradigm can be understood as the antithesis of the "traditional vertical integration model" where firm-level research and development activities lead to internally developed products/services that are then distributed by the firm [9].

As Huizingh [11] argues, the basic premise of open innovation is opening up the innovation process. One of its most often used definitions is: "the use of purposive inflows and outflows of knowledge to accelerate internal innovation (inbound open innovation), and to expand the markets for external use of innovation (outbound open innovation), respectively" [13]. These two types of open innovation are broadly studied in the relevant literature (e.g., see [13]).

While inbound open innovation refers to the acquisition of external technology in open exploration processes, and the practice of utilizing external sources of innovation, such as suppliers, customers, outbound open innovation describes the outward transfer of technology in open exploitation processes, and profiting from bringing ideas or technologies to market via pathways that lie outside the firm's [14–17]. Generally speaking, the literature shows that inbound open innovation is more frequently and commonly used and developed than outbound open innovation, which can be explained by insufficiencies of the market or the organization (see [11, 18, 19]).

2.2 Co-creation

The terms "co-production," "presumption," and "co-creation" refer to situations in which consumers/customers collaborate with companies or with other consumers/customers to produce valuable products and services. These situations sometimes appear to differentiate the traditional roles of "producer" and "consumer" [20]. It is extensively studied in the open innovation literature, and derived from open development studies [21], customization [7], and the like. According to the literature, however, the term "co-creation" only implies the mutual collaborative efforts/activities that occur during the consumption process, which was the original implication of presumption [22].

Customers/consumers become active participants in an open innovation process of a firm and take part in the development of new products/services [23]. Piller et al. [23] also focus on inbound innovation processes and find that the underlying idea, which is shared, is that of an active, creative, and communal collaboration process, between producers and customers/consumers. In their eyes, co-creation involves customers who are active in a company's innovation processes and initiatives [23, 24].

Furthermore, in the relevant literature, the term customer/consumer co-creation of value has been frequently used [25]. It was originally defined in the late 1990s by Kambil et al. [4] as co-creation of value by a firm's customers/clients. Then, this concept has been gradually extended toward other individual initiatives for customers and companies [7]. Some authors believe that the key to value creation is to co-produce goods/services that mobilize customers [26]. Matching customer practices and provider activities requires that one not only understands the concept of value but similarly prominently the process of value creation, especially through co-production activities [27].

Lusch et al. [28] provide a general model in order to explain that how much of the co-creation or service provision is performed by customers. Prahalad and Ramaswamy [29] argue that nowadays the marketplace has become a venue for proactive customer contribution. They argue for co-opting customer involvement in the value creation process. Moreover, Oliver et al. [30] elaborate the idea of co-creation in their remarks that marketing is headed toward a paradigm of real-time marketing, which incorporates mass customization and relationship marketing by interactively designing evolving offerings that meet customers' distinctive altering needs.

According to the notion of co-creation, if a consumer/customer is involved in the production of a good or rendering a service, the created value will be improved because the customer can modify the product as he/she desires. This is why co-creation concept refers to collaboration with customers for the purposes of innovation and has become a fundamental premise of the service/product development [31, 32]. Kristensson et al. [32] compare co-creation and customization and argue that the difference between these two lies in the degree of involvement of the customer; in general terms, the customer plays a less active role in customization than in co-creation. Finally, they conclude that based on the notion of co-creation, value can only be determined by the user during the consumption/usage process. von Hippel [33] studied the contribution of customers to the research and development of new products and services. His concept is broadly recognized in both academic and practitioner spheres. In 1970s, he found that most product innovations come not from within the company but from end users of the product [34, 35]. Moreover, Thomke and von Hippel [36] suggested methods for customers to become more like co-innovators and co-developers of custom products.

Value co-creation can take place only if interactions between the firm and the customer occur proactively. If there are no direct interactions, no co-creation of value is likely. However, the mere existence of interactions, by itself, does not mean that the firm is engaged in the customer's value creating process [37]. Lusch et al. [31] argue that an organization requires co-creation in order to renew its value propositions or offered services. In other words, it must be able to comprehend important external trends [22].

Customers play an active role in the creation and provision of services/products and in the realization of its value in different extents. Some customers may be involved with service activities and be regarded as "part-time employees" of the firm but all involved in integrating the service they receive with other aspects of their lives to some degree before there can be benefit. However, although firms are looking for increasing customer co-creation, it is crystal clear that customers normally fail to optimize their co-creation roles [38]. In sum, co-creation entails enabling users to freely experiment and innovate by providing a platform for collaborative innovation [39]. Prahalad and Ramaswamy [1] analyzed co-creation as a relatively new and critical development within the field of innovation. They provided examples of four building blocks by which co-creation occurs: dialog, access, transparency, and risk [40].

Piller et al. [23] suggest a typology of co-creation activities, which contributes to a better understanding of enterprise strategies for open innovation. Their first dimension describes the stage in the innovation process that customers can participate in. The second dimension refers to the degree of collaboration between a firm and its customers and among the customers themselves. The third dimension describes the degrees of freedom that customers are given when working on a specific task. Based on these dimensions, eight types of customer co-creation are identified [41]. This conceptualization, along with Chesbrough's [8, 9] conceptualization of open innovation, is used in the present study to answer a main question: "How open innovation helps companies in creating value through co-creation activities?"

3 Methodology

The qualitative researchers might aim at induction, in the sense of development of theory from data [42]. As Miller [43] notes, "Qualitative research is an empirical, socially located phenomenon, defined by its own history, not simply a residual grab-bag comprising all things that are not quantitative." This is a conceptual paper which puts forward a conceptual model for showing how open innovation helps companies in creating value through co-creation activities. For this purpose, co-creation is defined as a four-dimensional concept-based on the definition proposed by Piller et al. [23]. The arguments draw on a range of contemporary research prompted by considerations of the interface between co-creation and open innovation albeit that research into this area is still in its first two decades of elaboration. In particular, the discussion presented here uses data from:

Interview sessions Ten face-to-face interviews with experts in the field of co-creation and open innovation were conducted. The experts had more than three years of relevant experience and also published a series relevant of books, papers, and reports. As mentioned earlier, the aim of the research was to propose a conceptual for showing how co-creation activities help companies in creating value through open innovation. The interview agenda contained both structured elements and open questions [44].

Focus group sessions Two series of focus groups among experts were held which raised a variety of topics, including open innovation, characteristics of co-creation, etc. It should be noted that these sessions were designed based on [45] technique.

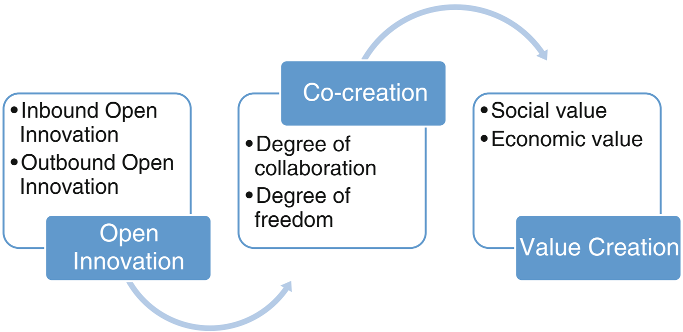

Fig. 1 Theoretical conceptual model (self-elaborated)

4 Discussion

As mentioned earlier, we used a qualitative research method to answer the research question. In order to do so, first the authors held ten face-to-face interview sessions with experts in this field to discuss the main topics, i.e., open innovation and its dimensions, co-creation strategies, value creation, etc. Then, two series of focus group sessions were arranged to decide what models are best fitted to answer the research questions. The length of the interviews ranged from 30 to 60 min, with a previous contextualization about the research. Almost all conversations were recorded, and the second interviewer was not actively involved in the interview process but took notes. There were some key issues which were mainly discussed in the sessions, among which the importance of the followings was greater than others: (1) to scrutinize the main frameworks, (2) to choose the main framework for the conceptualization of strategies, (3) to find examples of the real-world situations and discuss the used/proposed strategies, etc.

In sum, based on our findings, co-creation is a strategy to realize open innovation. In order to do so, both inbound and outbound open innovations are considered. Figure 1 shows that open innovation activities could influence co-creation activities/strategies, and it, in turn, will lead to social/economic value creation. However, this depends on some other issues, like contextual elements, readiness for innovation, etc. It should be noted that since the research was qualitative in nature, the authors tried to make a conceptualization based on which future studies could be done. Moreover, the gathered data were analyzed based on coding method, and then, the authors followed open and axial coding. The strategies mentioned in Table 1 are the main pillars under which the codes were categorized.

In Table 1, different scenarios are shown. As illustrated in the table, four main groups of strategies are identified, which are as follows:

Table 1 Different scenarios/strategies (self-elaborated)

			Co-creation			
			Degree of collaboration		Degree of freedom	
			Low	High	Low	High
Open innovation	Inbound open innovation	Low	Corrective product/service improvement	Incremental product/service improvement	Corrective product/service improvement	Incremental product/service improvement
		High	Crawling product/service improvement	Radical product/service improvement	Crawling product/service improvement	Radical product/service improvement
	Outbound open innovation	Low	Corrective product/service proposal	Incremental product/service proposal	Corrective product/service proposal	Incremental product/service proposal
		High	Crawling product/service proposal	Radical product/service proposal	Crawling product/service proposal	Radical product/service proposal

4.1 Corrective Product/Service Improvement/Proposal[1]

This group of strategies is appropriate for situations in which, (1) the open innovation level is low, and (2) co-creation is considered at a lower level. In such situations, companies collaborate with a single customer and use open innovation strategies at a low level. Then, they try to correct their product/services based on open innovation and comments from that single customer.

4.2 Incremental Product/Service Improvement/Proposal

This group of strategies is appropriate for situations in which, (1) the open innovation level is low, and (2) co-creation is considered at a higher level. These strategies are applicable when there is a group of customers or communities who collaborate with the company, but the company is not following strong open innovation strategies. Then, there would be some incremental product/service improvements/proposals.

4.3 Crawling Product/Service Improvement/Proposal

This group of strategies is appropriate for situations in which, (1) the open innovation level is high, and (2) co-creation is considered at a lower level. In this situation, the company follows highly open innovative strategies, but co-creation and customer collaboration are low. Therefore, the company considers Crawling product/service improvements/proposals.

4.4 Radical Product/Service Improvement/Proposal

This group of strategies is appropriate for situations in which, (1) the open innovation level is high, and (2) co-creation is considered at a higher level. These strategies are so radical and are followed by substantial changes in the company. This is because of the presence of a group of collaborative customers and the open innovation strategies of the company, which could make fundamental revisions in the products/services of the firm.

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[1] "Improvement" is used for inbound open innovations, and "Proposal" is used for outbound open innovations. The reason behind this is that when companies deal with inbound open innovations, they focus on themselves and "improvements", and when they follow outbound open innovation strategies, they focus on "proposals" to other external bodies/entities.

5 Conclusion

The literature on co-creation and open innovation is limited, as these concepts were newly discussed and elaborated in last two decades. However, there is evidence that supports the existence of these phenomena before, yet their conceptualization, as it is today, is new. This study, tried to answer the following question: "How open innovation helps companies in creating value through co-creation activities?" In order to do so, a qualitative study was done, which led to introduction of four types of strategies, as follows: (1) Corrective product/service improvement, (2) incremental product/service improvement, (3) Crawling product/service improvement, and (4) Radical product/service improvement.

Yet, there were some limitations. For instance, in this study, we mainly focused on the conceptualizations, and future studies could take the contextual elements into account to be more precise. Moreover, this research was a qualitative one and using quantitative methods could contribute to the existing literature. Last but not least, there were some limitations for finding experts in this filed, as the topic is new. To handle this limitation, we used snowball sampling to find the experts. Future research could be done in the domain of value created by co-creation activities. In particular, in developing countries, this concept is newly discussed and needs more efforts to be implemented (see [46, 47]). In addition, each scenario/strategy could be investigated separately to scrutinize how it works.

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Product, Organizational, and Performance Effects of Product Modularity

Henrike E. E. Boer

Abstract A lot has been written about the performance effects associated with implementing a higher degree of product modularity in a firm's product portfolio. However, these findings are mostly based on case research in the electronics and automotive industries and have hardly been tested and generalized beyond these industries. To be able to establish whether firms not part of these industries would experience the same performance effects, survey research will be needed. To support future survey research, this paper proposes an operationalization of product modularity and details the link between product modularity and firm performance, to support the future development of measures and hypotheses.

Keywords: Product modularity · Firm performance · Literature study

1 Introduction

The concept of modularity is not new. In fact, its origins can be traced back as far as to 1965, where Martin K. Starr noted that consumers were demanding ever-greater variety, a demand that could be met by modular production, that is, "developing capacity to design and manufacture parts, which can be combined in a maximum number of ways" [1, p. 132]. Plenty authors have further examined and developed the concept during the subsequent years.

Nowadays, most authors agree on the general principles behind modularity. In general, modularity is regarded as a design strategy for building and organizing complex systems effectively [2]. It is viewed as a relative property and depends on the degree to which the interfaces, interactions, or design rules of the system are

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standardized and the degree to which each product component has a clear, unique, and definite function within the system [3–5]. A system is modular if it has standardized interfaces and the components perform one or very few functions. In effect, the coupling and dependency between components are minimal, and the components can be mixed, matched, and changed without compromising the overall functionality and integrity of the system [3, 4, 6, 7].

The problem in the modularity literature is, however, that although many performance benefits have been proposed, these have hardly been tested empirically. One explanation for this lack of empirical verification has its roots in the concept itself. Even though authors agree on the general principles behind modularity, the concept of modularity is ambiguously understood on a more detailed level [8, 9]. Even within the boundaries of the management literature, the concept is measured and operationalized in different ways [10]. There is also a tendency in the literature to generalize findings based upon a limited empirical background [11]. The literature is riddled with examples of companies that have gained from using modular systems. However, most of the case studies derive from the automotive and electronics industries [12]. In addition, the few articles that have examined the performance effects of product modularity quantitatively have operationalized it differently (e.g., [12–19]).

Thus, in order to develop firmer theory, we need large-scale, i.e., survey based, research to (1) test the performance effects reported in the literature but largely based on case studies and (2) generalize these effects beyond the automotive and electronics industries. In order to prepare for such a study, this paper operationalizes product modularity and develops hypotheses on the performance effects of product modularity. This paper focuses on internal firm performance effects, which means that any possible effect that goes beyond firm boundaries, i.e., effects on supplier relations, customer involvement and preferences, or competitor imitation capabilities, is not included. The paper also primarily focuses on *product* modularity, not on service, knowledge, or production modularity, and on *operational* performance, not strategic or financial performance.

2 Research Design

In order to find the articles from which the many proposed performance effects of product modularity originates, a two-step literature study was conducted.

First, a subject search was conducted with the purpose to find articles that examined product modularity and its influence on firm performance. The search was conducted in four databases, confined to English language academic journals, limited to peer-reviewed articles, and reviews published during the last 20 years, and excluded obviously irrelevant areas such as chemistry, medicine, and physics. Based on the above search limitations and the search terms shown in Table 1, 649 articles were found.

Table 1 Search terms used in the literature search

Key words		Key words/title/abstract		Key words
Modular* OR	AND	Typology OR	NOT	Robot OR
Product platform OR		Classification OR		Software* OR
Product architecture OR		Operationalization OR		Programming OR
Product family		Performance OR		Coding OR
		Benefit OR		Psychology OR
		Benefits OR		Bio*
		Effect OR		
		Effects		

Table 2 Measures used in survey research in the modularity field

Measures	Definition
Decomposability and assemblability	The ease to which the product can be decomposed and assembled
Independence	The ability to make changes to key components without changing others
Commonality and carry-over	The ability to reuse components between products and across product generations
Combinability and add-on	The ability to combine and add-on components to create different end products
Other	Standardization of components and processes, use of modular design and use of a standard base unit or technology

This number was reduced to 25 articles by only including articles focusing on *product* and *firm* level and excluding articles that focused on models, metrics, and methods for assessing and achieving modularity, on modularity's performance effects in a very specific context or regarded modularity as one of many ways of achieving certain effects. All of these 25 articles had some preconceptions of how product modularity influences firm performance, either based on logic or on previous articles.

The purpose of the second step was to extend the number of articles and include those that were most influential in forming the preconceptions behind modularity. To do so, the 25 articles' references were turned to. From these references, the 21 articles, books, and paper cited five times or more were added to the literature base.

3 Linking Product Modularity and Firm Performance

Only a handful of articles have attempted to operationalize modularity. These articles, shown in Table 3, are based on survey research. Although they examine different industries and settings—from the first-tier suppliers to the "big three" auto manufacturers in North America [18, 19] to the plastics, electronics, and toy

Table 3 Performance effects reported based on survey research

Article	Findings	Product modularity measures
[13]	Product modularity positively impacts delivery, flexibility, or customer service, but is not correlated with low price and product quality	Decomposability Independence
	Delivery and flexibility are significantly correlated with product performance, but is not correlated product quality, low price and customer service	Commonality Carry-over
[14]	Product modularity positively impacts product innovativeness, flexibility, and customer service, but is not correlated with low price, product quality, or delivery	Standardization of components
	Internal integration and product modularity will interact to significantly improve product innovativeness and has a marginal effect on product quality	
[15]	Product modularity positively impacts NPD time performance, which is moderated through internal integration	Modular design and assemblability
	Findings do not support the existence of a significant moderating effect of supplier involvement	Commonality
[16]	Product modularity positively impacts NPD time performance and product performance, which is moderated through internal integration	
[17]	Plants with product modularity exhibited significant higher levels of supplier integration and component inventory and higher use of captive retail outlets	Combinability Add-on
	Customer involvement in the assembly and use stages (not in the fabrication stage) and product modularity is significantly correlated with the use of make-to-stock production planning	Commonality Standard base unit or technology
[18]	Product modularity positively impacts manufacturing agility, firm growth, and use of process modularity	
	Process modularity has no impact on manufacturing agility, and manufacturing agility had no impact on growth performance	
[19]	Product modularity has a significant effect on every integration strategy	Modular design and combinability
	Product modularity positively impacts costs, quality, flexibility, and cycle time	Standardization of processes and components
	Product modularity and design/supplier integration will interact to significantly improve flexibility and has a marginal effect on costs	
	Product modularity and manufacturing integration will interact to significantly improve flexibility and has a marginal effect on costs and cycle time	

(continued)

Table 3 (continued)

Article	Findings	Product modularity measures
[12]	Product modularity positively impacts financial performance	Decomposability Independence
	Product modularity positively impacts product variety, but is not correlated with new model and product introduction	Commonality
	Modular structures and processes have direct effects on financial performance, independently of product modularity	Carry-over

industries in Hong Kong [13, 14]—the articles present some comparable findings. First of all, it is found that product modularity positively impacts one or more traditional performance parameters, such as flexibility, customer service, product performance, product innovativeness, and new product development speed, and may or may not influence costs, new product and model introduction, delivery, and quality. Secondly, it is established that the relationship between product modularity and performance is mediated by internal integration.

However, problem is that the findings are based on different measures of product modularity. As illustrated in Table 3, the different authors that have conducted survey research have used different measures to operationalize product modularity. These measures are defined in Table 2.

Furthermore, the above measures ignore some critical aspects of product modularity. Ulrich [4], one of the most referred to articles, defines a modular architecture as having a one-to-one mapping from functional elements to physical components and decoupled interfaces between components. However, both the allocation of functions to the modules and the interfaces has been neglected in the measures.

Yet another problem is that the articles operationalize product modularity by focusing, mostly, on its effects, rather than its characteristics. The extent to which components can be reused, added-on, or carried over are product *effects* of implementing modularity in the product portfolio, while standardization of modules and interfaces, and one-to-one (or few) links between modules and functions are actual *characteristics* of modularity.

Lastly, these findings are based on different and very aggregate perceptions of what performance exactly constitutes. In fact, the relationship between product modularity and firm performance is rather complicated. The complexity of this relationship may partly explain why researchers struggle with determining the exact nature of the connection between product modularity and, for instance, innovation, quality, and costs [20, 21]. This means that there is a need for combining and clarifying what literature proposes the relationships between product modularity and firm performance to be, in order to develop hypotheses to support future research. This article will try to do so, by distinguishing between (1) the *organizational* effects that are expected to derive from and/or enhance the

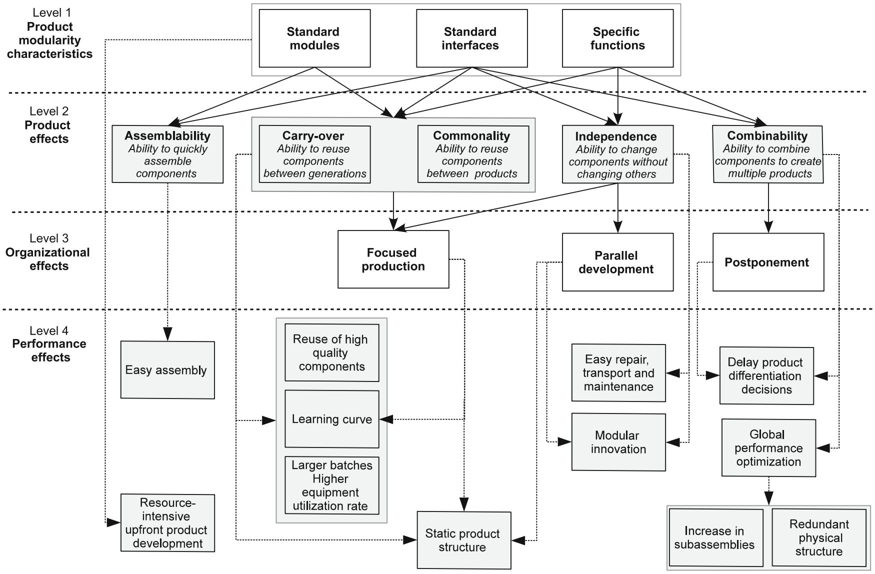

Fig. 1 The link between product modularity and firm performance

proposed performance effects and (2) *performance* effects to be expected from implementing product modularity and these organizational practices.

The remainder of the article is structured according to the model shown in Fig. 1. This model delineates between product modularity *characteristics* and product *effects* and also distinguishes between *organizational* effects and *performance* effects that possibly could be expected to appear after implementing product modularity.

3.1 Product Modularity Characteristics and Effects

This article proposes that product modularity is a function of three product characteristics: the standardization of component interfaces and the component itself and how functions are allocated to the components. This means that the extent to which a firm's product portfolio is modular depends on whether the physical components and connections are standardized and the internal integrity in the product. Standard interfaces refer to the use of physical connections that are well defined and not allowed to change during a period of time [3, 23]. Standard components are components that are designed for the use in several products [4]. Internal integrity refers to consistency between function and structure [24], i.e., the extent to which each component performs one of few functions. If key product functions are dependent on multiple components, it gravely complicates the task of standardizing components or subsystems and their usability in multiple applications [4].

The use of standard interfaces and modules provides the company with several possibilities, which it may or may not utilize. First of all, it allows the existing and future product portfolio to use the same component in several products for the same functional purpose, i.e., it allows for carry-over and commonality. It also facilitates assemblability, as it minimizes the complexity of assembly as the number of components is minimized, and interfaces are well known.

The use of standard interfaces and specific functions enables product changes to one functional element to be localized within one component, which is denoted independence in Fig. 1 [4]. It should also allow the product to be decomposable, i.e., that the product cannot only be quickly assembled, but also quickly decomposed into separate units again, which facilitates a "plug-in and plug-out flexibility." The combination of standard interfaces and specific functions also helps attaining combinatorial assembly from relatively few components, that is, combinability [4], allowing the "mixing and matching" of components to give a potentially large number of product variations [25].

3.2 Organizational Effects

The combinability of components allows for form [26] or manufacturing postponement [27]. Postponement is based on the principle of seeking to design common platforms, components, or modules, and delaying final assembly or customization until the final market destination and/or customer requirements are known [28]. It implies that the customer order decoupling point, the point that divides the order-driven, and the forecast-driven activities, is pushed upstream [26], in the form of, for instance, assemble-to-order.

Product modularity not only allows for the decoupling of components, but also the decoupling of tasks [29]. This enables product development, after the system-level design phase, to be conducted by relatively independent teams [7]. Different parts of the design can be worked on independently and parallel to each other [5]. In other words, when a firm creates modular designs with well-defined interfaces, the need for component developers to interact is greatly reduced, which enables a firm to adopt a "modular" organization design for product creation processes [3]. Similar effects can be expected in production, where modular designs allow a firm to divide its production into specialized groups with narrow focus areas [4].

3.3 Performance Effects

One of the most mentioned benefits of product modularity is the possibility to achieve economies of scale on component level [30]. Reusability allows the components to be produced in higher volumes using larger batch sizes [29]. This means that change over times and costs are reduced and a higher equipment utilization rate can be expected. In addition, development resources and capital expenses can be amortized across a larger range of units [29], lower spare parts, and safety stock levels are needed and, if the component is outsourced, larger batches can be purchased at increasing discount rates. The performance effects that can be expected from achieving component economies of scale include lower unit manufacturing costs, shorter manufacturing lead-time, and higher-throughput time efficiency.

Related to economies of scale is the notion of the learning curve. Reusing components means that the total number of *different* components to be manufactured decreases and the workforce will attain a comparatively higher degree of experience with producing the specific components, especially if they are reused in different product generations. As these components, carried over from previous generations, have already been tested extensively in practice, product modularity may increase durability and reliability. Additionally, if the components that are carried over are of proven high quality, a firm can expect lower scrap and rework costs and higher conformance and product quality.

Another performance effect of product modularity highlighted in the literature is related to postponement [4, 18]. A greater variety of products can be constructed from a smaller set of components [29], tailored according to customer order, and assembled or configured to order. The bulk of the components, rather than final products, can be stocked [29], resulting in shorter-order lead-times and improved responsiveness for customized products, and also decreased inventory costs, as fewer variants need to be, kept in stock [31].

The assemblability and decomposability of the product facilitated by product modularity, enables easier, and therefore, less costly and faster assembly. The ability to decompose the product also supports repair and maintenance, as any dysfunctional element can easily be removed and replaced, reducing rework cost [29].

The relationship between product modularity and innovation is more ambiguous than the above relationships and much discussed in the literature. On the one hand, product modularity, especially the independence of components and parallel development, facilitates incremental and modular innovation. Concurrent development of components may increase the efficiency of product development and time to market [5, 23]. Additionally, modular upgradable products enable economies of substitution, where technological progress may be achieved by substituting certain components while retaining the others [6]. The components that are retained in the product structure can, subsequently, undergo a series of incremental improvements.

Through developing new and improved components based on new technologies that fit into the overall product architecture and by giving component developers the opportunity to experiment with new component designs, the innovativeness and introduction speed of new technologies can be accelerated [2, 23]. This enables the firm to offer greater product variety and customize products to suit many different customer segments [32].

However, it is important to note that, although modular innovation may enhance performance at the module level, it does not necessarily do so on system level [33]. Excessive modularization may result in enhanced system complexity from the perspective of the designer, where the designer may become blind to possible important interactions between component improvements and system-level performance [33].

Even though modularity may facilitate rapid innovation, firms will also experience resource-intensive upfront development before being able to make use of these benefits, as the initial design efforts needed to create a modularized product portfolio are much higher than designing comparable integrated systems [2], and may include design changes in the manufacturing system, too [32]. It requires extensive architectural knowledge to be able to define which components and interfaces need to be standard and establish how functions can be allocated to components.

Finally, a modular product portfolio does not imply sustainable advantages. From time to time, not only the components, but also the entire product structure may require an update. Innovation at this level, also called architectural innovation, can be difficult for firms geared toward innovation on a modular level, as these firms over time will have developed organizational structures and information channels that are focused on component-level activities [25]. So, architectural innovation creates problems for the established firm, as it alters the way in which the components of a product are linked together [34].

Another side effect of increasing product modularization is that components are not optimized for one application but have been designed so that they meet the requirements of multiple products. This is called global performance optimization in Fig. 1, and means that, compared to integral products, the individual products that are part of a modular product portfolio may have lower levels of performance or that components have excess capability when used in some particular applications [29]. An integral product allows for function sharing, i.e., implementing multiple functions using a single element, which allows for redundancy to be eliminated and geometric nesting minimizing the mass, size and material use of a product [7]. Modular product portfolios, on the other hand, may have redundancy in the physical structure, increasing size and mass, material use and in the end, variable costs. The fact that there is less function sharing in modular products may also increase the number of subassembly steps needed in production.

Finally, modularity has also been highlighted as a tool to achieve mass customization and is seen as a part of platform thinking. Pine [30] even states that creating modular components is the best method of achieving mass customization—minimizing costs, while maximizing individual customization. Meyer and Lehnerd [35] argue that companies should plan and manage on the basis of product platforms, the combination of subsystems and interfaces that constitute a common product structure for a series of derivative products. The clearly identified interfaces between subsystems of the product would then provide the product designers with the degree of freedom needed for rapid and cost-efficient creation of derivative products [35].

4 Summary and Further Research

4.1 Summary

There is little robust theory on the practical effects of implementing a higher degree of product modularity in a company's product portfolio. In order to test this, mostly case research based, findings reported in the literature and establish whether the many benefits suggested extend beyond the automotive and electronics industries, large-scale survey research is needed. To support such research, this paper proposes an operationalization of product modularity and details the link between product modularity and product, organizational, and performance effects, to support the future development of measures and hypotheses.

Operationalization of product modularity and its effects By taking outset in the measures used in survey research as well as the most widely recognized definitions, this paper proposes that product modularity should be operationalized by including (1) its characteristics—the degree of standardization of interfaces and components and the degree of internal integrity within the product portfolio—and (2) its product, organizational, and performance effects. *Product effects* include the degree to which the firm can carry-over or reuse its components between products and product generations, and the independence, combinability, and assemblability of components. *Organizational effects* include (1) moving the customer order decoupling point upstream by implementing assemble-to-order or even configure-to-order production, (2) decoupling of activities in product development, as well as (3) focused, i.e., specialization of, production activities. The extent to which these effects are implemented affects the extent to which *performance effects* are achieved, in terms of, for example, shorter-order lead-times, improved responsiveness, decreased inventory costs, and increased speed, and reduced cost of new product development.

The role of time It takes time and money to implement and make the best use of modularity. Creating modularity requires a large amount of upfront development costs as well as resources. Modularity facilitates incremental and modular innovation. However, over time, architectural innovation could be needed, which may be difficult to cope with for a company whose performance is based on an established architecture. Finally, the learning curve effect is fostered by the reuse of standards, both in terms of modules and interfaces, which, in the long run, improves speed, quality, reliability, and, thereby, reduces costs.

4.2 Further Research

Figure 1 together with the operationalizations proposed in this article will provide the basis for the development of a survey questionnaire. In preparing that instrument, the role of context needs to be addressed as well, considering that, for example, product modularity may prove to be overkill in very stable markets and in markets where there is no need for high product variety. In environments with very volatile changes in, for example, product technology, or demanding very levels of high customization, modularity may not be the appropriate solution, either. As Ernst [11] highlights, a feature of modular systems is their rigidity, as interface standards are difficult to adjust. Any transition to a new generation of design architecture requires fundamental changes in system components, and if these transitions are required too often, product modularity may not be the correct solution [11].

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Production and Resource Scheduling in Mass Customization with Dependent Setup Consideration

Izabela Nielsen, Grzegorz Bocewicz and Ngoc Anh Dung Do

Abstract Mass customization has been implemented in services and manufactures to increase the competitiveness of companies. In a manufacturing company, the procedure for production and resource scheduling has to be changed to adapt to mass customization. A good production and resource scheduling will contribute to the success of mass customization. This paper addresses the problem of production and resource scheduling for a production system with dependent setup and internal transportation such as AGVs in a mass customization environment. A constraint-programming-based methodology is developed to satisfy the customer demands on-time. An example is presented to illustrate the performance of the proposed methodology.

Keywords Mass customization · Resource scheduling · AGVs scheduling · Production scheduling · Dependent setup

1 Introduction

Nowadays, customers prefer highly customized products and require their orders to be fulfilled quickly [5]. Large variety demands make difficulty in planning and fast reacting when getting orders from customers (online rescheduling). Changing from traditional production policy where high-leveled customization is produced with high production cost [3, 9] to mass customization which can reduce production cost while keeping the same quality of product and on-time delivery to

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satisfy diversified demands will bring success to the company [4]. In mass customization, using flexible manufacturing systems including advanced manufacturing machinery such as computer numerical control (CNC), robots, and automatic guided vehicles (AGVs) can provide a high output rate, easily change to producing similar products, and quickly fulfill the orders of customers with high-customization and low-production cost. Improving the efficiency of supply and distribution chains helps the manufacturer to follow the production plan and to deliver products on-time. However, in mass customization, production managers have to deal with large variety, small batch sizes, random arrival of orders, and wide span of due dates [13] while keeping the production costs as low as mass production. Moreover, it is not easy to use the traditional method to schedule and allocate resources in production planning when manufacturers change to the implementation of mass customization. In a manufacturer, several production policies are implemented such as make-to-order, make-to-stock, etc., but they are not relevant to mass customization. For example, make-to-order policy is inefficient because it does not utilize the similarity and modularity of products and makes higher production cost than mass production. Make-to-stock gets trouble with the large variety. These limitations bring a challenge to the development of a new approach for production and resource scheduling in mass customization. There are many researches in production planning and scheduling which vary from simple to complicated production line. Some of them concern the use of AGVs or mobile robots in production. Optimizing the schedule for both machine and AGV is very difficult, and it is more complicated for the case of multiple AGVs due to avoiding the collision of AGVs when they are moving. On the other hand, the sequence of products to be manufactured is an issue because of customization. In mass customization, the demand on products cannot be counted as the total demand during planning horizon. It means that an amount of a product has to be delivered at a certain point of time in the planning horizon and the deadline of producing a product is considered in making the production plan. Therefore, the production manager has to decide on a production scheduling which can satisfy the demand on-time and what the resource scheduling is so that the corresponding output rate (production rate) can guarantee producing enough products to satisfy demand. Optimizing production scheduling is more difficult when the setup is dependent on cost and time. Different production sequences can make different make-spans due to dependent setup, which affects the delivery time. In mass customization, the manager has to decide when and how many units of a type of product to be produced regarding the deadlines of delivery.

In this paper, we consider the problem of production and resource scheduling for a production system where mass customization is implemented. The setup time and cost are dependent on the sequence of products, and there exists internal transportation (e.g., AGVs). The production plan must assure that the demands from customers are satisfied on-time. It is less efficient if production scheduling (e.g., product sequence) and resource scheduling (e.g., AGVs scheduling) are not simultaneously considered. This paper is aimed to develop a novel methodology to deal with both production and resource scheduling with dependent setup in a mass customization environment. This paper is organized as follows: in Sect. 2, we present the motivation of this paper; the description of considered system is shown in Sect. 3; the problem formulation and solution algorithm are presented in Sects. 4 and 5; an example is provided in Sect. 6 to illustrate the performance of proposed algorithm; and this paper ends with the conclusion in Sect. 7.

2 Motivation

In this paper, a production system, which includes a set of machines and a set of AGVs to transport semi-finished goods among the machines, is considered. Different products have different sequences of production processes. When the production system changes to producing another type of product, the machines need to be setup and this setup is dependent meaning that the required cost and time for setup depend on the sequence of two products. There are two main problems in this system. The first one concentrates on how to make a production plan to satisfy the customer demand in a planning horizon considering sequence-dependent setup. This problem is a well-known NP-hard problem. Many studies are conducted on these problems for single machine or parallel machines with or without sequence-dependent setup [1, 6, 7]. The second main problem is the AGVs scheduling problem. The aim of AGV scheduling is to dispatch a set of AGVs to achieve the goals for a batch of pickup/drop-off (or P/D for short) jobs under certain constraints such as deadlines, priority, etc. [8, 10]. Bocewicz (2014) considers the problem linking AGVs and production scheduling, which is treated as a scheduling of concurrent cyclic multimodal processes. To solve it, the multi-level declarative framework is implemented using constraint-programming techniques. It is more complicated if we consider mass customization manufacturing that is characterized by short product life cycles with large mix and low-volume products in a rapidly changing environment [13]. The production system has to change frequently to satisfy the large variety of demands and utilize the automated machines such as CNC and AGVs to rapidly change to producing new product. Therefore, the manager has to consider the production plan including production scheduling and resource scheduling. However, these two problems are considered independently in traditional production system. The contribution of this paper is to develop a methodology to make a plan for production scheduling and resource scheduling simultaneously with dependent setup in mass customization.

3 Systems of Concurrent Cyclic Processes (SCCPs)

The problem of production and AGVs scheduling is based on the AGVs system shown in Fig. 1a. The digraph shown in Fig. 1b represents AGV system from Fig. 1a) where six **cyclic local** processes $P_1 - P_6$ encompassing AGVs operations

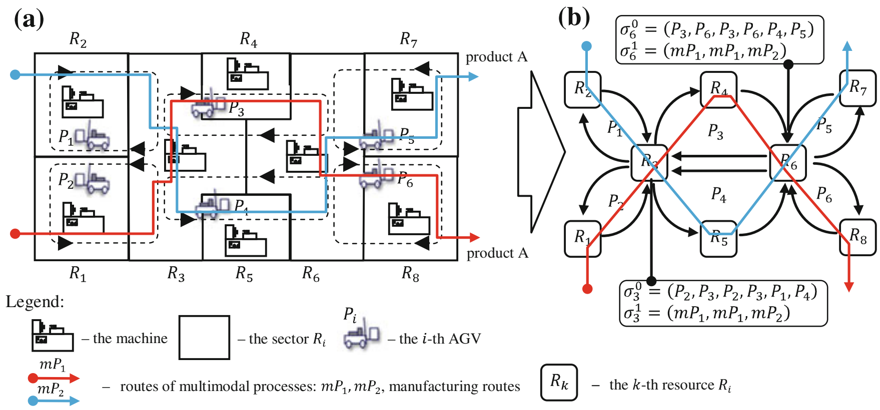

Fig. 1 The example of AGVs system (**a**) and its SCCP model representation (**b**)

are distinguished. Processes passing transportation sectors (resources) interact via common shared resources. Their routes are specified as follows: $p_1 = (R_2, R_3)$, $p_2 = (R_1, R_3)$, $p_3 = (R_3, R_4, R_6)$, $p_4 = (R_3, R_5, R_6)$, $p_5 = (R_6, R_7)$, $p_6 = (R_6, R_8)$, where: R_3, R_6—are shared resources, since each one is used by at least two processes, R_1, R_2, R_4, R_5, R_7, R_8—are non-shared as each one is exclusively used by only one process.

Apart from local processes, we consider two concurrent **multimodal processes** (representing manufacturing routes [2]): mP_1, mP_2. In these kinds of processes, the execution of operations is realized commonly with appropriate operations of local processes. In other words, processes are executed along the parts of cyclic local processes. The routes of considered multimodal processes are distinguished by red mP_1, and blue mP_2 color lines, in Fig 1. Processes represent two manufacturing routes which are used for mass production of two kinds of products (distinguished as products A and B). The multimodal process route specifying how a multimodal process is executed can be seen as the composition of the route parts of local cyclic process. So, the routes mP_1, mP_2 are: $mp_1 = ((R_1, R_3), (R_3, R_4, R_6), (R_6, R_7))$, $mp_2 = ((R_1, R_3), (R_3, R_5, R_6), (R_6, R_7))$, where: (R_1, R_3), (R_3, R_4, R_6), (R_6, R_7)—parts of routes p_2, p_3, p_6 included in mp_1, (R_1, R_3), (R_3, R_5, R_6), (R_6, R_7)—parts (subsequences) of routes p_1, p_4, and p_5 included in mp_2.

Both, local and multimodal, processes interact on the basis of mutual exclusion protocol while sharing common resource (transportation sector). The possible resource conflicts are resolved with the help of assumed priority-dispatching rules determining the order in which processes make their access to common shared resources. For instance, in case of the resource R_3, the priority-dispatching rules: $\sigma_3^0 = (P_2, P_3, P_2, P_3, P_1, P_4), \sigma_3^1 = (mP_1, mP_1, mP_2)$ (see Fig. 1b) determine the orders in which local and multimodal processes can access to the shared resource R_3. A sequence σ_3^0 means that the first access is for process P_2, and next to P_3 and once again to P_2, and next P_3, P_1, P_4, and so on. So, the SCCP is specified by the following pair of dispatching rules: $\Theta = \left(\Theta^0, \Theta^1\right), \Theta^0 = \left\{\sigma_1^0, \sigma_2^0, \ldots, \sigma_6^0\right\}$ (for local processes), $\Theta^1 = \left\{\sigma_1^1, \sigma_2^1, \ldots, \sigma_6^1\right\}$ (for multimodal processes). Besides resource conflict resolution, the priority rules determine the frequencies of mutual appearance of local processes. For instance, in case of $\sigma_3^0 = (P_2, P_3, P_2, P_3, P_1, P_4)$, it means in one cycle processes P_2 and P_3 are repeated twice while processes P_1 and P_4 only once. In general case, the set of dispatching rules Θ implies the sequence of relative frequencies of local processes mutual executions denoted by $\Psi = (\Psi^0, \Psi^1)$, $\Psi^l = \left(\psi_1^l, \psi_2^l, \ldots, \psi_n^l\right)$, where: $\psi_i^l \in \mathbb{N}$—determines the number of relative, i.e., in relation to other processes, $P_i(\text{for } l = 0)/mP_i(\text{for } l = 1)$ occurrence. In case of SCCP from Fig. 1b, the following sequence is assumed: $\Psi = \left(\Psi^0, \Psi^1\right)$where: $\Psi^0 = (1, 2, 2, 1, 1, 2)$ and $\Psi^1 = (2, 1)$.

In general case, local $P_i \in P = \{P_1, P_2, \ldots, P_i, \ldots, P_n\}$ and multimodal $mP_i \in mP = \{mP_1, mP_2, \ldots, mP_i, \ldots, mP_w\}$ processes execute periodically while following the route $p_i = \left(p_{i,1}, p_{i,2}, \ldots, p_{i,lr(i)}\right)/mp_i = \left(mp_{i,1}, mp_{i,2}, \ldots, mp_{i,lm(i)}\right)$ (where: $lr(i)/lm(i)$—a length of cyclic process route, $p_{i,j}$, $mp_{i,j} \in R$, $R = \{R_1, R_2, \ldots, R_m\}$.

Let us assume that: $o_{i,j}/mo_{i,j}$—denotes the j-th operation executed by the process P_i/mP_i along the routep_i/mp_i, and $t_{i,j}/mt_{i,j}$ $\left(t_{i,j}, mt_{i,j} \in \mathbb{N}\right)$, denotes the time of the operation $o_{i,j}/mo_{i,j}$ execution. In the considered case, the operation times of local processes $T_i = (t_{i,1}, t_{i,2}, \ldots, t_{i,lr(i)})$ and times of all multimodal operations $mT_i = (mt_{i,1}, mt_{i,2}, \ldots, mt_{i,lm(i)})$ are the same. Using the above notation, an SCCP can be defined as a tuple [2]:

$$SC = ((R, SL), SM) \tag{1}$$

where: $R = \{R_1, R_2, \ldots, R_c, \ldots, R_m\}$—the set of resources, $m = |R|$; $SL = (ST_L, BE_L)$—the structure of local processes; $ST_L = (U, T)$—the variables describing the layout of local processes; $U = \{p_1, p_2 \ldots, p_n\}$—the set of routes of local process, $n = |U|$; $T = \{T_1, T_2, \ldots, T_n\}$—the set of sequences of operation times; $BE_L = (\Theta^0, \Psi^0)$—the variables describing the behavior of local processes; $\Theta^0 = \left\{\sigma_1^0, \sigma_2^0, \ldots, \sigma_c^0, \ldots, \sigma_m^0\right\}$—the set of priority-dispatching rules; $\Psi^0 = \left(\psi_1^0, \psi_2^0, \ldots, \psi_n^0\right)$—the sequence of relative frequencies of mutual executions of local processes; $SM = (ST_M, BE_M)$—the structure of multimodal processes; $ST_M = (M, mT)$—the variables describing the layout of the level of a multimodal process; $M = \{mp_1, \ldots, mp_i, \ldots, mp_w\}$—the set of routes of a multimodal process, $w = |M|$; $mT = \{mT_1, mT_2, \ldots, mT_w\}$—the set of sequences of operation times in multimodal processes; $BE_M = (\Theta^1, \Psi^1)$—the variables describing the behavior of multimodal processes; $\Theta^1 = \left\{\sigma_1^1, \sigma_2^1, \ldots, \sigma_c^1, \ldots, \sigma_m^1\right\}$—the set of priority-dispatching rules for multimodal processes; $\Psi^1 = \left(\psi_1^1, \psi_2^1, \ldots, \psi_w^1\right)$—the sequence of relative frequencies of mutual executions of multimodal processes.

4 Problem Formulation

The behaviors of system (1) can be seen as a cyclic schedule representing the cyclic production of product A and B. Formally, the cyclic schedule of SCCP is defined in following way [2]:

$$X_{SC} = ((X, \alpha), (mX, m\alpha)) \tag{2}$$

where: $X = \{X_1, X_2, \ldots, X_i, \ldots, X_n\}$—the set contains the sequences $X_i = \left(x_{i,1}, \ldots, x_{i,\psi_i^0 \cdot lr(i)}\right)$ which elements $x_{i,j}$ determine the moments of operation $o_{i,j}$ beginning in the l-th cycle: $x_{i,j}(l) = x_{i,j} + l \cdot \alpha$, $l \in \mathbb{Z}$, $(x_{i,j}(l) \in \mathbb{Z}$—the moment when the operation $o_{i,j}$ starts its execution in the l-th cycle, α—denotes the periodicity of local processes: $\alpha = x_{i,j}(l+1) - x_{i,j}(l)$. $mX = \{mX_1, \ldots, mX_i, \ldots, mX_w\}$—the set of sequences, $mX_i = \left(mx_{i,1}, \ldots, mx_{i,\psi_i^1 \cdot lm(i)}\right)$, where: $mx_{i,j}$—variable specifying the value $mx_{i,j}(l)$: $mx_{i,j}(l) = mx_{i,j} + l \cdot m\alpha$, $l \in \mathbb{Z}$, $m\alpha$—denotes the periodicity of multimodal processes: $m\alpha = mx_{i,j}(l+1) - mx_{i,j}(l)$.

Figure 2a shows the graphical representation of the cyclic schedule X_{SC} corresponding with a possible production mode of system from Fig. 1. In this mode, two streams of process mP_1 and one stream of process mP_2 are finished in one cycle. In other word, two units of product A and one unit of product B are completed within 14 units of time (u.t.) (14 u.t.—is a periodicity of one cycle of mode I). In that context, the rate of product A of mode I is equal to two: $rp_{A,1} = 2$ units/period and rate of product B is equal to one: $rp_{B,1} = 1$ units/period. Modes II and III (Fig. 2b, c) are characterized by different periodicity: $\alpha_2 = 16$ u.t. and $\alpha_3 = 12$ u.t. and different production rates: $rp_{A,2} = 1$ unit/period; $rp_{C,2} = 2$ units/period (mode II) and $rp_{B,2} = 2$ units/period; $rp_{C,2} = 1$ unit/period (mode III).

In the case of SCCP, the problems of rescheduling (problem of cyclic behavior transitions) between many different cyclic schedules play a special role. In Fig. 3, the example of transition between the schedules of modes I and II is presented. Considered transition allows finishing the production of products A and B (mode I) and start new ones C and A (mode II). Please note that a transition requires an additional delays (the setup times) caused by a preparation of resources to new operations. The duration time of the transition from Fig. 3 is equal to 31 u.t. ($st_{1,2} = 31$) and the production rates: $rp_{A,1,2} = 2$ units/period and $rp_{B,1,2} = 2$ units/period.

Of course, similar transitions are possible for the rest variants: Mode II → Mode I; Mode I → Mode III, Mode III → Mode I, Mode II → Mode III, Mode III → Mode II. All of them were evaluated using approach based on the finding the states with common allocation of processes [2] and presented as a digraph on the Fig. 4. In that context, we consider the following problem:

Given is SCCP described by SC (1), non-empty set of admissible cyclic schedules $X_{SC,i}$ (2) of SC: $AX = \left\{X_{SC,1}, X_{SC,2}, \ldots, X_{SC,l_{AX}}\right\}$ described by the

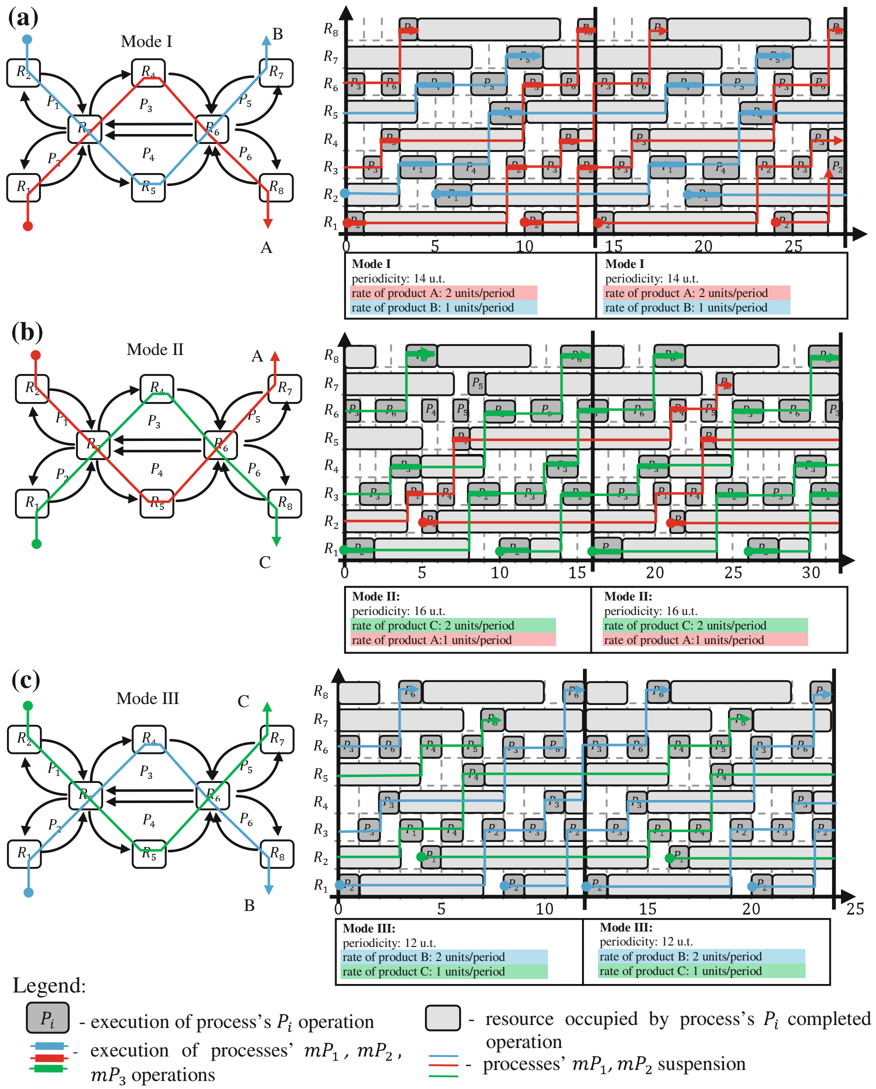

Fig. 2 Local and multimodal processes cyclic schedules for SCCP from Fig. 1b

periodicities α_i and production rates $rp_{A,i}$, $rp_{B,i}$, $rp_{C,i}$, etc.; non-empty set of admissible transitions between schedules AX: $AT = \{TR_{1,2}, TR_{1,3}, \ldots, TR_{(l_{AX}-1),l_{AX}}\}$ described by the setup times $\alpha_{i,j}$ and production rates $rp_{A,i,j}$, $rp_{B,i,j}$, $rp_{C,i,j}$, etc.; digraph describing relations between elements of sets AX and AT (see Fig. 4).

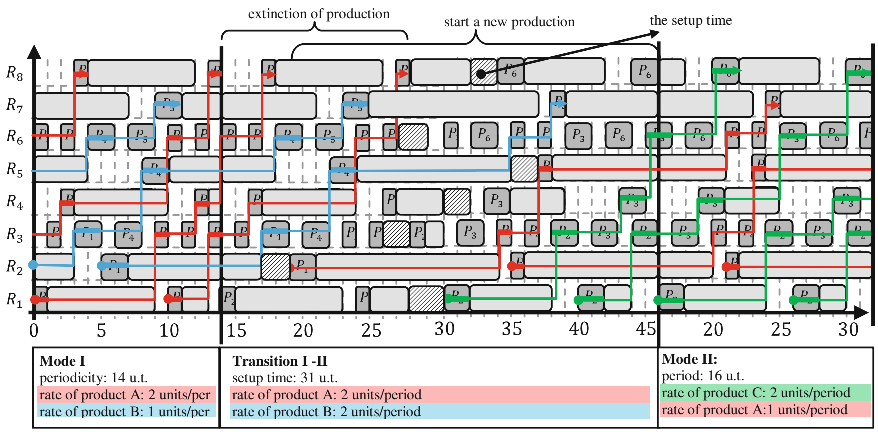

Fig. 3 An example of transition from mode I to mode II

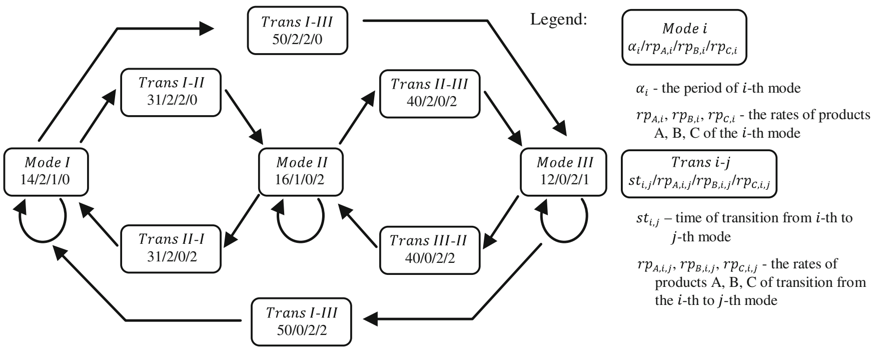

Fig. 4 A digraph of admissible transitions between modes of SCCP form Fig. 1b

Question: "Does there exist the schedule of SCCP (treated as a compositions of schedules AX and transitions AT) which guarantee production of product *A*, *B*, *C*, etc., on the given level RA, RB, RC in given horizon times HA, HB, HC?"

5 Declarative Approach

Constraints' satisfaction problem (CSP) can be used as a formal representation of the stated problem. Consider CSP (6):

$$\mathrm{CS} \;= ((\{V, \mathrm{PA}, \mathrm{PB}, \mathrm{PC}, \mathrm{PT}\}, \{D_V, D_{\mathrm{PA}}, D_{\mathrm{PB}}, D_{\mathrm{PC}}, D_{\mathrm{PT}}\}), C) \tag{3}$$

where: V, PA, PB, PC, PT—decision variables: $V = (v_1, v_2, \ldots, v_i, \ldots, v_{lv})$—the sequence of SCCP modes, v_i—the production mode executed in i-th cycle of

SCCP, lv—number of considered cycles of SCCP. In the case of SCCP from Fig 1, a system can achieve one of nine modes: modes I, II, III ($v_i = 1, 2, 3$) and transitions I–II, II–I, II–III, III–II, III–I, I–III ($v_i = 4, 5, 6, 7, 8, 9$, respectively),

$$\mathrm{PA} = (pa_1, pa_2, \ldots, pa_i, \ldots, pa_{lv})\text{---the sequence of production level of product } A,$$
$$pa_i\text{---the production level of product } A \text{ after the } i\text{-th cycle of SCCP},$$
$$\mathrm{PB} = (pb_1, pb_2, \ldots, pb_i, \ldots, pb_{lv})\text{---the sequence of production level of product } B,$$
$$pb_i\text{---the production level of product } B \text{ after the } i\text{-th cycle of SCCP},$$
$$\mathrm{PC} = (pc_1, pc_2, \ldots, pc_i, \ldots, pc_{lv})\text{---the sequence of production level of product } C,$$
$$pc_i\text{---the production level of product } C \text{ after the } i\text{-th cycle of SCCP},$$
$$\mathrm{PT} = (pt_1, pt_2, \ldots, pt_i, \ldots, pt_{lv})\text{---the sequence of the finish times of SCCP modes},$$
$$pt_i\text{---the finish time of the mode } v_i,$$
$$D_V, D_{\mathrm{PA}}, D_{\mathrm{PB}}, D_{\mathrm{PC}}, D_{\mathrm{PT}}\text{---the domains describing the values of decision variables}:$$
$$v_i \in \{1, \ldots, 9\}, pa_i, pb_i, pc_i \in \mathbb{N},$$

C—the set of constraints describing the relations between the executed modes of SCCP (V, PT) and production levels (PA, PB, PC). Constraints C are determined by the digraph from Fig. 4 and given of production level and horizon:

$$(v_1 = i) \Rightarrow \left[\left(pa_1 = rp_{A,i}\right) \wedge \left(pb_1 = rp_{B,i}\right) \wedge \left(pc_1 = rp_{C,i}\right) \wedge (pt_1 = \alpha_i)\right], \quad v_1 \in \{1, 2, 3\}, \quad i = 1, 2, 3 \tag{4}$$

$$\left(v_j = i\right) \Rightarrow \left[\left(pa_j = rp_{A,i} + pa_{(j-1)}\right) \wedge \left(pb_j = rp_{B,i} + pb_{(j-1)}\right) \wedge \left(pc_j = rp_{C,i} + pc_{(j-1)}\right) \wedge \left(pt_j = \alpha_i + pt_{(j-1)}\right)\right], \quad i = 1, \ldots, 9, j = 2, \ldots, lv, \tag{5}$$

$$\left(v_{(j-1)} = 1\right) \Rightarrow (v_1 \in \{1, 4, 9\}), \left(v_{(j-1)} = 2\right) \Rightarrow (v_1 \in \{2, 5, 6\}), \tag{6}$$

$$\left(v_{(j-1)} = 3\right) \Rightarrow (v_1 \in \{3, 7, 8\}), \left(v_{(j-1)} = 4\right) \Rightarrow (v_1 = 2), \quad j = 2, \ldots, lv, \tag{7}$$

$$\left(v_{(j-1)} = 5\right) \Rightarrow (v_1 = 1), \left(v_{(j-1)} = 6\right) \Rightarrow (v_1 = 3), \left(v_{(j-1)} = 7\right) \Rightarrow (v_1 = 2), \tag{8}$$

$$\left(v_{(j-1)} = 8\right) \Rightarrow (v_1 = 1), \left(v_{(j-1)} = 9\right) \Rightarrow (v_1 = 3), \quad j = 2, \ldots, lv, \tag{9}$$

$$\left(pt_j \geq HA\right) \Rightarrow \left(pa_j \geq RA\right), \left(pt_j \geq HB\right) \Rightarrow \left(pb_j \geq RC\right), \tag{10}$$

$$\left(pt_j \geq HC\right) \Rightarrow \left(pc_j \geq RC\right), \quad j = 1, \ldots, lv, \tag{11}$$

The solution of CS problem is a sequence V representing schedule of SCCP modes and sequences PA, PB, PC, PT the values of which satisfy all constraints C (4)–(11). To solve this kind of problem, the constraint-programming environments ILOG, ECL^{i}PS^{e} [12], Mozart are used [2, 11].

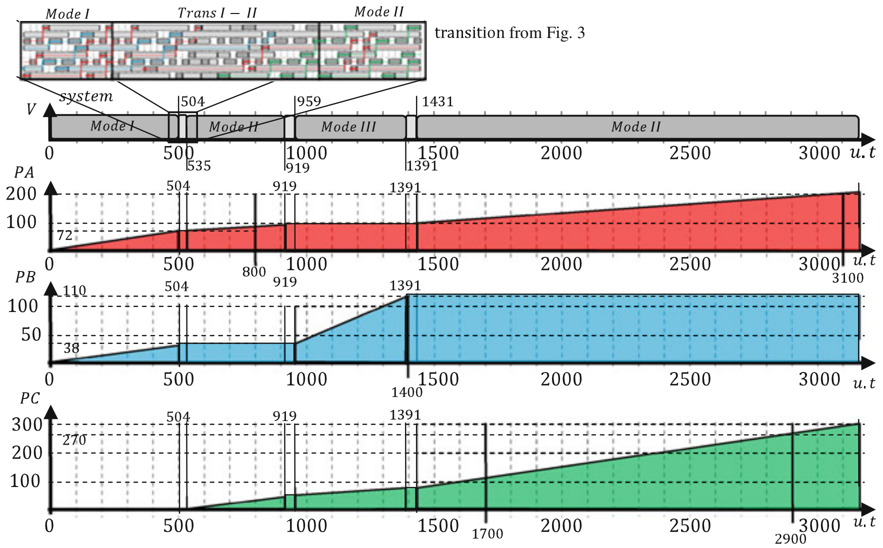

Fig. 5 The admissible solution of problem CS (3)—the schedule of SCCP (Fig. 1b) modes *V*

6 Illustrative Example

An SCCP shown as Fig. 1 is given. It can work in three modes (see Fig. 2) with transactions presented on the Fig. 4. Three kinds of products: *A*, *B*, *C* should be produced according to the following limits (determined by the customer requirements):

- product *A*: 70 units within 800 u.t. and 200 units within 3,100 u.t., $RA_1 = 70$; $HA_1 = 800$; $RA_2 = 200$; $HA_2 = 3{,}100$;
- product *B*: 110 units within 1,400 u.t., $RB = 110$; $HB = 1{,}400$;
- product *C*: 100 units within 1,700 u.t. and 270 units within 2,900 u.t., $RC_1 = 100$; $HC_1 = 1{,}700$; $RC_2 = 270$; $HC_2 = 2{,}900$;

The answer to the following question is sought: "Does there exist a schedule of SCCP (a sequence *V*) which guarantees the production of product *A*, *B*, *C*, on given levels RA_1,RA_2 RB, RC_1, RC_2 in given horizon times HA_1, HA_2 HB, HC_1, HC_2?"

The one admissible solution is shown in Fig. 5. It has been obtained in OzMozart, Dual Core, 2.67 GHz, 4.0 GB RAM environment in 7 s (25,438 steps of constraint propagation and variables distribution). The presented schedule allows satisfying all given production constraints.

7 Concluding Remarks

In this paper, production and AGVs scheduling in mass customization are considered. The combination of production and AGVs scheduling in mass customization has not been studied, and this paper proposes a methodology to fill this gap. A procedure based on CSP is developed to find a solution which satisfies the constraints on production level and time horizon. Modeling problem as CSP and implementing it by constraint-programming techniques can reduce computation time to adapt with random orders which frequently occur in mass customization. By satisfying the product-level constraint, the solution guarantees to fulfill the large variety of demands. On the other hand, by satisfying the time horizon constraint, the solution assures that the products are on-time delivered to the customer, and this will increase the competitiveness of the manufacturer. Moreover, the lower production costs increase competiveness and profit. The application of this paper is very promising as: (1) the methodology can be implemented to mass customization production systems; (2) it assists the manufacturer to reduce cost when changing production system and plan for mass customization; (3) the proposed procedure can obtain a feasible solution very quickly (within 7 s in the illustrated example). This paper can be extended by developing a methodology for online control and fuzzy control where unforeseen situations occur, for example production line break-down or order changing from key customers.

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Scaling Up Local and Individualized Solutions, Challenging Existing Logic

Nicola Morelli

Abstract This paper is based on a recently completed EU-funded project, aimed at creating location-based and socially networked services to support elderly people's independent life. The project team created a platform of services for elderly people in four EU locations. It included the development of a business model to ensure the economic sustainability of the services beyond the funding period. Elderly people, as commonly known, are reluctant to use new technology and are especially diffident of open social networking systems, because of the openness of those systems, that risk to undermine the urgent need of trust and safeness. The Life 2.0 platform is highly related to a real-life context of senior people. This has implications on the scalability of the platform. This paper analyses the lesson learned and proposes some insights into how the diffusion of innovation based on local and personal solutions challenges the common scalability logics.

1 The Logical Context

Demographical and social transformation are challenging the social and economic structure of our communities, imposing a deep review of the strategies to address existing and emerging social needs.

One of the main evidences of such changes is the unbalance between active and passive population, caused by broad social and economic phenomena, such as unemployment, migration and population ageing. This will require a radical revision of welfare policies and a radical redesign of public services [1, 2].

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One of the emerging issues for government and public institutions is the need for a revision of assistance services and infrastructures for senior people. A proportionally larger number of elderly people are going to require a bigger amount of resources, but the present economic crisis and the growing disproportion between active and passive citizens is urging governments to consider a new approach to services that considers supporting senior people as much as possible in their own home [3].

The existing welfare services are grounded on the idea that elderly people be passive receivers of assistance, unable to perform many fundamental functions in their everyday life. This in fact represents a limit of the existing system, because it does not consider that the senior population is very diverse in its components, their capabilities are different; many people in the third age may not have the physical strength of their youth, but they still have enormous residual capabilities and resources, including time, knowledge and skills that are sometimes disappearing.

Several governments are considering activating citizens' residual capabilities to co-produce new solutions. This approach would bring institutions closer to citizens' needs and possibly offer higher service quality for a proportionally lower cost [4].

This methodological approach has been used in the Life 2.0 project to develop an online platform to support social interaction, thus facilitating the exchange of knowledge and favours, supporting the organization of individual and group initiatives and even individual entrepreneurship.

The experience in the Life 2.0 project, however, suggests an interesting challenge that possibly concerns several other services that are based on an active participation of individual citizens to the process of value creation.

The economic sustainability of highly personalized and localized services, like Life 2.0, requires a new approach to scalability, so that the knowledge and resources used in an individual instance of the service can also be reused and replicated in other contexts or for other communities. The condition of personalization and the strong link to the local context makes the traditional idea of a *wildfire* diffusion of the service totally inadequate. One can no longer expect those services to increase the number of users from a small community to millions of users, as it happened for several social networking applications that were basically geographically independent.

The considerations about the possible replication and expansion of the Life 2.0 platform suggest some interesting insights into alternative scalability strategies.

2 The Life 2.0 Project

At the end of 2010, a group of 12 partners, including universities, organizations, companies and public administrations, started an EU-funded project called Life 2.0. The project aimed at generating service-based solutions to support elderly people's independent life, through a platform that is exploring the advantages of geographical positioning systems and social networking.

The project, now almost completed, is proposing interesting insights to understand how a different kind of innovative solutions can be scaled up from local to wider geographical contexts.

The Life 2.0 project has been carried out in four different locations: Aalborg (Denmark), Joensuu (Finland), Barcelona (Spain) and Milano (Italy). In each of those locations, a group of 20–40 elderly people has been contacted and involved in the co-development and testing of a platform of online services.

The level of participation of elderly people to the project has been very high, with continuous feedbacks on the design of the platform components. The co-creation process reinforced users/testers' sense of ownership to the platform, besides creating a strong social and human link with the project personnel.

In two cases (Aalborg and Barcelona), the project has been associated to an existing community: in Aalborg, the project has been located in a training centre, where elderly people meet daily or weekly, to make physical exercise, knit, play cards, discuss or have dinner together. In Barcelona, the project has been placed in "Agora", an association of volunteers located in the area of Sant Marti, where elderly people attend courses and meetings. In Finland and Milano, the community of elderly people has been "created" around the local library, with the help of existing organizations operating in the area. As a result of the project, groups of users have been formed (in Milano and Joensuu) or reinforced (in Aalborg and Barcelona) beyond the online contact between them.

3 What is Life 2.0?

The Life 2.0 platform is the playground for a series of activities and exchanges of knowledge, information and help between elderly, local associations/organizations, and local businesses. The platform includes three main components:

- **Announcements**: here, people can offer or request help to others. The nature of such help is usually very different. According to the seniors that tested the platform, it is sometimes hard to classify posts in this category as "help": they could range from real help to solve IT problems to the proposal to walk together to the church or the supermarket.
- **Events**: here, local organizations (the local church, activity centres, associations and clubs) can post announcements of initiatives and events that happen in the neighbourhood
- **Market place**: here, local businesses can post ads or even proposals for personalized services, such as special menu of the day, special offer of the week, to elderly people in the area.

The access to the platform is strictly regulated in each location, by a local administrator that only accepts users if they are personally or directly known. For the duration of the project, the administrator is a researcher from the project, but in the post-funding period, the administrator should be a person that personally knows the users or is able to have enough knowledge about the users to guarantee trust in the community. Usually, personnel of an activity centre, or associations, can have this role.

About 40 people in each community are using the Life 2.0 platform at present. Some organizations are posting relevant events and some businesses (e.g. local foot massage, local supermarket or a national producer of aids products) are posting ads (but not yet personalized offerings) on the platform.

4 Main Features and Limitations of the Life 2.0 System

The main feature of the project is the strong link between online presence and direct and personal contact between the users. The Life 2.0 platform has never been proposed as an alternative to personal contact. Users were well aware of the existence of social networking platforms, such as Facebook, and in few cases, they also had a profile in some social networks. However, users considered those platforms quite impersonal unsafe and unattractive, because they are open, they refer to very broad contexts, beyond the geographically perceivable limits of their everyday life, and because those networks link unknown or unfamiliar people.

The platform is strongly linked to everyday real life. Life 2.0 services help people organizing a walk to the local supermarket, solving practical problems, organizing parties and supporting seniors in many other practical functions. This means that the platform is complementary, rather than alternative to real life. The platform makes the condition possible, for an *augmented neighbourhood*, in which the increased knowledge about what is going on in the area is giving more opportunities to solve practical problems, but also to reinforce social cohesion.

The other characteristic of the platform is the direct personal contact between people in the community and the community administrator. This ensures trust among people and between people and the platform, which has been identified by the testers as a critical requirement.

This characteristic is at the same time a positive feature of the system—because it encourages elderly peoples' participation—and a limitation of the platform—because the limits of the community correspond to the number of people that are personally known by the administrator. This feature has been critical when shaping the scalability and business model.

5 Evaluation Criteria for Life 2.0

Evaluation criteria for this platform are qualitative and not obvious; because of the high social and cultural implications, the service has on elderly people's life. Two parameters that may be used for an evaluation are *relevance* and *trust*.

5.1 Relevance

As many other social networking applications, the value of the Life 2.0 platform could be measured by users' participation in the platform. Users' participation is not necessarily proportional with the amount of information or activities posted on the platform, nor is this parameters linearly linked to the number of registered users. In other words, the platform can include a lot of information without being relevant to users, or it can include a lot of users, but being used by only few of them.

In this platform, as in any online environments, an enormous amount of information available is not necessarily absorbed and used in everyday life. A platform full of information would require elderly people to dedicate more attention to it and therefore would inevitably put Life 2.0 in competition to their everyday life, their personal and social needs. The dialectic interaction between over abundance of information, whatever relevance it may have, and users' filter generated by their attention resources can be analysed as an economy of attention [5, 6]. This approach is very relevant for the business framework for the Life 2.0 project.

In fact the Life 2.0 platform can also be seen as the marketplace in which information-based service offers will meet users' attention. Relevance will be the main catalyst for user attention. Attention is the internal currency in the exchange of information within the platform.

Not only will the services need to have high and personal relevance for users, but also the platform itself. This is the reason why the content of the platform cannot just have a functional and commercial character (e.g. services to elderly people); but it has to include information (e.g. events, mutual help offering or simply communication opportunities) the value of which can hardly be quantified in economic terms. Elderly will pay more attention to what is relevant for their everyday life, when the online content of the platform will seamlessly mix with their real life. Of course their direct participation to the definition of the content (in the form of calls for participation, recommendations, help offering and even service offering to their neighbours) will increase their attention resources spent on the platform. Elderly people's chances to be directly involved in each activity will be a filter for the offerings on the Life 2.0 platform. At the same time, the possibility for elderly people to generate content on the platform will widen the window of attention for the services offered in the platform.

5.2 Trust

Trust is linked to the number of users connected to the platform, their social proximity and their geographical location.

As mentioned before, trust is a basic requirement for elderly people to be part of the platform. Given the strong link of the platform to the local context, trust can be

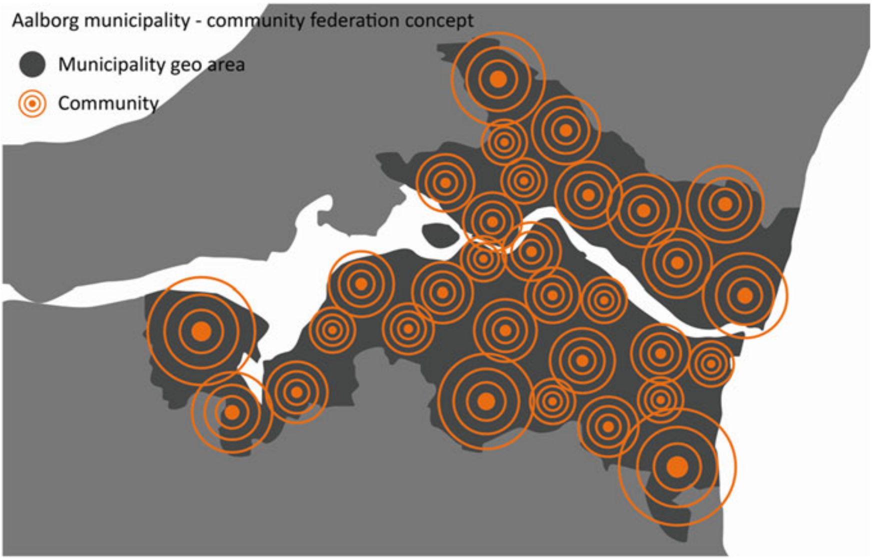

Fig. 1 Diffusion model for Life 2.0 for the Aalborg pilot

achieved by making sure that the online presence is parallel and overlapping with the real interaction between people in a neighbourhood. Trust is also ensured by the presence of an administrator, or a centre, where the participants are known and can be identified by a person. This means that the expansion of the model cannot be wide and seamless, but has to progress by "circles" or communities (Fig. 1). Each community will guarantee trustworthy interaction to its users. When the online community becomes larger than the number of people the administrator knows personally, no new users can be added, unless another community or another "centre" is set up, with a new administrator. Of course, there could be overlapping between two different communities, but the participation of a user to more than one community has to be mediated by the administrators.

Both the parameters illustrated above, relevance and trust, suggest that the strategies to scale up the Life 2.0 platform cannot be based on a generic model of diffusion of innovation. Instead of a "wildfire" innovation pattern, those parameters suggest a development "by community". It is not the number of users that should expand to scale up Life 2.0, but the number of communities.

6 The Life 2.0 Ecosystem

The Life 2.0 business model is based on a modular structure. The modularization is based on capabilities, knowledge and skills. Each module describes an actor type in the system and its role. Here, below and in Fig. 2, the modules and their characteristics are described.

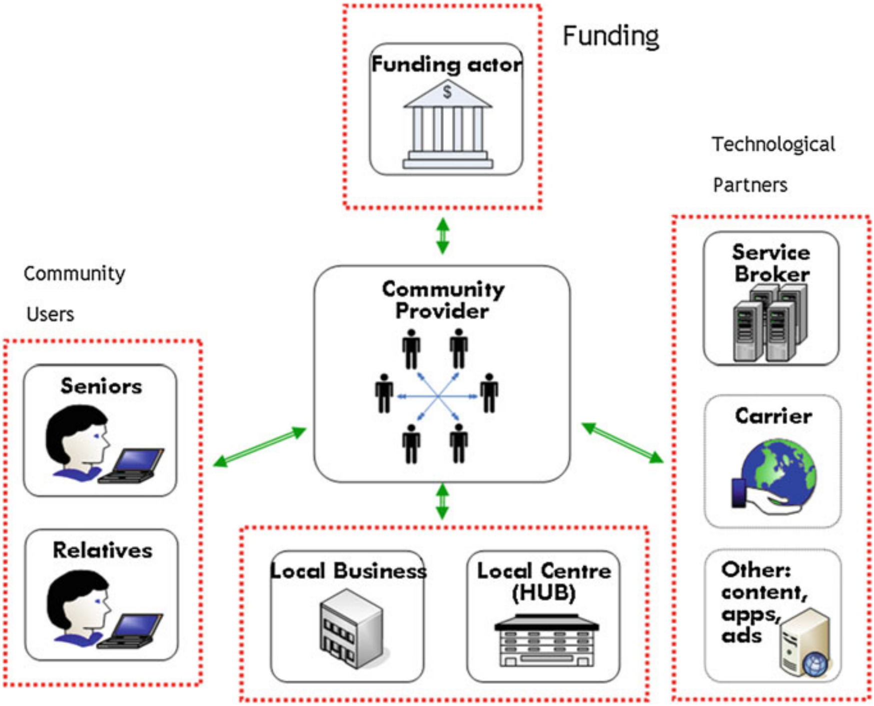

Fig. 2 The Life 2.0 ecosystem (source Life 2.0)

6.1 Users

Users are typically elderly people living in a specific area, but this category of users can also include relatives (children, grandchildren) or friends, of elderly people. Users are not supposed to pay to access the platform, but of course, they should pay for accessing the services offered on the platform by local business (e.g. restaurant, training).

Capabilities: Beside their economic capability, that allows them to access to the commercial services offered on the platform, their main "currency" in this platform is *attention*. Their attention, measured by the amount of their posts, answers to others' posts or active participation and adds value to the platform.

Knowledge: elderly people provide personal, un-codified knowledge, concerning social links, events, initiatives and geographically located information. The relevance of this knowledge is often local, that means that the value they can add to the platform is also strongly related to their location.

Skills: elderly people have often limitations in using IT facilities; to address this, the platform has been co-designed with them, to make sure its technical characteristics matches the users with the lowest technical skills.

6.2 Community Providers

The community providers are organizations (e.g. seniors' associations, local interest groups) or public entities (such local municipalities), that are able to aggregate a number of senior citizens, thus becoming the tangible reference for the users of the Life 2.0 platform.

Capabilities: Community providers usually have a physical location, where events or gathering are organized. Their role is to moderate, promote and ensure trust among the users. Community providers should *own* the platform at the local level.

Knowledge: Community providers have the critical social knowledge that would allow the network to be formed and grow. They have the basic function of aggregating people. Without this knowledge, the mere existence of an IT platform for exchanging information would not have too many chances of success among elderly people. The personnel in this organizations indeed has personal and direct knowledge of all the members of the network and can moderate and encourage the participation in the activities on the platform.

Skills: The skills of personnel working at community providers are not necessarily technical; they may not be able to manage complex technical problems (such as installation of the platform, updates and new applications). For those operations, they need the support of technical brokers. Community providers should also collect money from the sponsors; however, small organizations may not be legally or organizationally fit for this, and therefore, they may need the support of external organization or a *federation* of community providers. In some cases, like in Denmark, this role can be covered by local administrations that coordinate different activity centres.

6.3 Event Organizers/Hub

The project team defined with the term *hub* all the organizations around which the local everyday life of elderly people is usually based. Hubs include local associations, training centres, sport clubs and churches. Most of the hubs are not supposed to pay to access the platform, although some of them (local cinema, theatre, bowling), may be requested to pay a fee to access the service.

Capabilities: Likewise community providers, hubs are organizations and groups that aggregate people, but their function in the platform does not concern the coordination of the activities. Hubs add content to the platform in the form of public events or initiatives for a larger number of users (users can also organize events, but those events are usually for a restricted number of people).

Knowledge: Hubs have a good social understanding of the local area and interpret the need for entertaining, spiritual, sport or social activities. Their knowledge is usually localized, although some events may have a wider relevance and connect different communities

Skills: usually, people from hubs adding events to Life 2.0 do not have high technical skills. In many cases, the contributors from hubs are themselves elderly people and have the same need for simplicity and clarity as users.

6.4 Local Businesses

Local businesses included in the platform are usually small commercial activities that users already know personally, such as foot massage, local supermarket or local restaurants. Those business activities can reach elderly people with personalized offers (e.g. the menu of the day) or with online services (such as booking/payment) that can supplement personal services. However, some of those businesses may have wider target group and therefore be interested in participating in a system that is broader than a single community. Also their contact with the system may not directly come through community providers, but through a "coordinator" of such providers, such as local administrator or a federation of community providers. Local businesses are supposed to pay to access the platform.

Capabilities: Local businesses are adding value to the platform in the form of:

- Real personalized services proposed to citizens
- Ads targeting users in a community or across communities
- Money paid to the platform administration to access the platform

Knowledge: Local businesses provide content to the platform in the form of codified knowledge, technical skills and specialized services to elderly people.

Skills: Although many people in local businesses do not have high technical skills, those actors are supposed to have a more active role in the platform. In long terms, they are supposed, for instance, to develop applications that may be connected to Life 2.0 through appropriate API; such applications will be essential to support personalized services.

6.5 Technical Broker

Technical brokers are the actors that will install the platform at the local level and ensure a constant technical support to community providers. In some instances though, technical brokers may be the *owners* of the platform and promote it to local communities.

Capabilities: Technical brokers are adding value to the platform by providing their technical support. They may also develop new applications that address emerging needs from customers.

Knowledge: likewise the social knowledge of community providers, the technical knowledge needed to run the platform is essential for the existence of the platform. In some cases, technical brokers may integrate the platform in their existing offering to local communities.

Skills: Technical brokers are not supposed to have high social skills, that means that their capability to reach users may be limited, especially for the target group of elderly people. Their technical skills are complemented by the community providers' social skills.

6.6 Funder

Because of the initial installation costs, and constant personnel costs, the Life 2.0 platform may need to be supported by a funder organization that could be a public or private institution. In some instances, this role could be covered by public administrations. In this historical moment in fact, consistent cuts in the public budget are common to many local administrations; however, the Life 2.0 platform offers elderly people a concrete possibility to activate local resources, such as other elderly people, their families, their neighbours; that would ensure a better life quality and a sense of independence.

Capabilities: Besides the financial capabilities, that would add immediate support to the platform, the funding organization could have a more active role, as catalyzer of new communities and coordinator of the financial support for a federation of communities. In this role, they could also reinforce the trust in the individual community providers.

Knowledge: Although no particular knowledge is required from this actor, the funding organizations may provide knowledge and skills to set up new communities. Furthermore, their back up to a community provider may ensure trust among the users.

Skills: Funders should add the financial skills that would allow community providers to operate, especially in the earliest phases of the project.

7 Discussion: Models for Scaling Up the Life 2.0 Platform

The description of the ecosystem and its actors clearly shows a direct and tight link between the online and the real community. These characteristics describe a sort of *hybrid* social network, in which logical, geographical and personal relationships are equally relevant. Each instance of the platform is anchored to a real and local context, because the information it includes is also local and very personal to its users. However, not all the actors are necessarily focusing on the same geographical context. Local businesses, for instance, may find a single community too limited and would not consider accessing to the platform, unless they have access to multiple communities. The same applies for hubs, although most of them do not pay. Even elderly users may find the community limiting, if they live in border areas between two communities or have friends in communities where they do not live. The need for relevance and trust, however, would make a “wildfire” development of the platform unthinkable. A Life 2.0 community cannot exceed the number of people the administrator knows personally. Other mechanisms have obviously been considered, such as invitation and referral, but the participants were diffident to forms of diffusion that would widen the network beyond their local community. They explicitly declared that the advantage of this platform, with respect to other open social networking applications, is the fact that its access is limited and controlled.

Unlike many other online social networking applications, which are independent from the geographical context in which the participants are located, Life 2.0 can only expand if new ecosystems are set up in different local context. The community provider is the catalyst for each ecosystem. All the other actors will connect with the community providers.

Local business or technical providers may take part to more than one community, as they need to reach larger group of users. Those actors are still working to scale up their services, whereas other actors, such as the community providers are working to *defend the borders* of the community. The two logics, however, are not competing, they are rather complementary: a strong community, with a strong participation, will increase users’ attention, and therefore give more value to each post or paid service offered by the business companies in the platform. On the other hand, technical providers or local businesses taking part to a community could act as *bridge users* of the platform, as new community providers may use their presence in their area to build a new network.

The question of new models for scaling up similar cases for social innovation is quite new to the literature. Many authors have focused on social network potential to generate social innovation [7, 8], but they did not propose any broad reflection on a model to scale up innovation generated by social networks. The innovation they mention is either relying on existing social networks or assumes that the diffusion of new applications will follow a logic of wildfire expansion. The parameters of relevance and trust have been considered also critical for the diffusion of social networks, but the link to the geographical location has never been considered as a binding condition for scaling up, but rather an outcome of specific approach to the use of such applications.

The question of scalability has been analysed from a technical perspective; Pujol et al. [9], for instance, focus on strategies that replicate *bridge users* to scale up fully distributed systems. Although this approach focuses on the technical organization of online social networks, without any reference to the social characteristics of its users, the exploration of the parallel development of scaling-up strategies for fully distributed ICT systems and *hybrid* social networks, such as Life 2.0, could provide interesting insights.

8 Conclusion

The dynamic proposed by the Life 2.0 project and its model of expansion is challenging the existing logic to scale up innovation.

The existing model is based on the most known examples of diffusion of applications, such as Facebook or Twitter. Those applications were relying on logical links between participants (interest, friendship, collaboration), but were basically geographically independent, although the geographical proximity of the participants was an obvious reason for establishing new friendships on those networks.

The new model instead is deeply rooted in the geographical context. The social links often exist before the creation of the application and the application is usually *augmenting* the existing links, adding a new layer of information. The two fundamental parameters for the creation of such network do not hinder scaling up, but impose a new mechanism of expansion.

Scaling up Life 2.0 is not an obvious exercise, because it requires that the ecosystem be appropriately structured according to the modular structure suggested in this paper and the roles and competences of each of the actors are clearly defined. Of course, the Life 2.0 project represents just a case, but the conditions it represent may be common to many other cases in which services, especially public services, are designed to address personal or very local instances. The time is coming for rethinking the way public and private services should be planned and scaled up from local contexts to wider geographical areas, and Life 2.0 proposes some critical reflections on how this can be done.

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Strategic Capabilities to Manage High-Variety Production Environments: The Role of Underlying Activities and Organizational Resources

Frank Steiner and Moritz Wellige

Abstract Product offerings (PO) with a high number of product variants have become a standard in today's industrial manufacturing sector and are also becoming increasingly popular in business-to-consumer markets. Increasingly, more companies pursue such a strategy as they hope to benefit from the competitive advantage that arises from the opportunity to address every customer individually. However, adapting a respective business model (BM) for high-variety (HV) production demands profound organizational change. Existing research suggests that companies have to develop certain strategic capabilities when implementing such business strategies. Still, most studies lack a sufficient level of detail in the discussion of these strategic capabilities and remain vague regarding underlying management activities and organizational resources. With this study, we provide more detailed definitions of the strategic capabilities of mass customization. Furthermore, we identify a comprehensive set of underlying management activities and organizational resources and thereby facilitate the realization of the strategic capabilities for practitioners.

Keywords Mass customization · Strategic capabilities · Management activities

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1 Introduction

The development of suitable product offerings (PO) for today's markets is strongly affected by the level of uncertainty within the particular product domain [1–4]. In this context, market uncertainty oftentimes is the result of changing customer demands with regard to specific product requirements [3, 5]. Furthermore, today's markets are characterized by an increasing heterogeneity in customer needs [6]. In consequence, POs with a high number of product variants have become rather common for manufacturing companies. This trend can be observed in particular in industrial goods' markets, as customers in such business-to-business (B2B) settings usually demand products that meet clearly defined specifications [7]. Such a "lock-in" on strictly defined product specifications typically results in low levels of customer flexibility and an increasing demand for product variety [8, 9]. Being confronted with such business environments, manufacturers of industrial goods need to establish new business models (BM) that are capable of dealing with high levels of customer demand heterogeneity. Mass customization (MC) is such a BM that aims at establishing a competitive advantage by addressing every single customer individually [10–12].

However, adapting a respective BM for high-variety (HV) production cannot be accomplished overnight, but demands profound organizational change [13–15]. Existing research suggests that companies have to develop certain strategic capabilities in order to be able to successfully implement such business strategies for HV environments. Salvador et al. [16], for example, suggest three dimensions of strategic capabilities for the successful implementation of a MC BM, namely "solution space development" (SSD), "robust process design" (RPD), and "choice navigation" (CN). Despite the availability of an ample amount of literature that discusses success factors or strategic capabilities for the implementation of a MC BM, the adoption rate of such business approaches is still surprisingly low [17]. We assume that the reason for this development can be found in a lack of sufficient detail in the understanding of the necessary capabilities as well as related management activities and organizational resources. Even though there is a broad body of literature available, most studies fail to provide necessary managerial implications for companies that would like to increase the variety of their POs. By addressing these shortcomings of current research, we make important contributions to the field of MC or HV production environments in general: (1) This research extends and refines the definitions of strategic capabilities for BMs related to HV production strategies. (2) Based on literature reviews and expert interviews, this paper provides an extensive list of managerial activities and resources that can strengthen a company's ability to provide a HV PO.

2 Theory and Literature Review

In recent years, a growing number of companies have established BMs and strategies, which are geared toward product customization and HV production, also referred to as MC [18, 19]. Numerous examples of successful applications, which range from the automobile industry [16] and engineered products [20] to electronics [21, 22], demonstrate the high relevance as well as the practicability of such strategies. Thus, customization strategies represent a promising option for companies competing in long-tail markets that are typically characterized by heterogeneous customer needs. However, the examples also show that some companies are more successful than others in the realization of BMs for HV environments. This leads to the question, whether there are certain prerequisites that facilitate the implementation of BMs for HV productions. A review of the literature dealing with HV production strategies and associated BMs reveals different management activities, procedures, and capabilities, which are regarded as critical for a successful implementation [cf. 16, 18, 23]. For example, the literature highlights the need for flexible but also efficient manufacturing processes for the realization of large numbers of product variants [cf. 24–27]. The discussion also includes aspects such as the necessary interaction between firms and their customers during the specification of an individual product [12, 18, 28–30]. A third relevant factor is concerned with the PO: As offering limitless choice is economically unfeasible, companies need to identify those product attributes for which the customers require variety [16, 31–33]. This is in line with the resource-based view, which locates the source of company success in the existence and composition of certain resources and capabilities. Differences in performance and divergence in competitiveness between companies are due to imperfect distribution of resources across companies [34–37]. Thus, each company represents a unique bundle of resources that determines its competitive position [38]. In this context, resources are defined as specific tangible and intangible assets owned by companies and—if they are difficult to imitate—represent a potential source of a sustainable competitive advantage [39].

We follow the notion that capabilities are also representing a particular type of resource [37, 40]. Capabilities enable companies to improve the productivity of the ordinary resources a company possesses [40]. As Amit and Schoemaker [38] point out, capabilities "[…] are information-based, tangible or intangible processes that are firm-specific and are developed over time through complex interactions among the firm's resources". Thus, capabilities enable companies to orchestrate activities and utilize resources in an efficient and purposeful way. Subsequently, the combination of resources and capabilities that are available in a company determines its ability to successfully realize a BM for heterogeneous markets. We expect that an analysis of the resources and capabilities that companies use in the pursue of a customization strategy may provide valuable insights into why some firms perform better than others.

3 Strategic Capabilities for Customization Strategies

In order to get an overview of existing research on strategic capabilities, underlying activities, and routines for customization strategies, a literature review was conducted. On the one hand, the review shows that there are only very few studies that take a holistic perspective on MC. Instead, most studies focus on single capabilities or specific underlying activities and organizational resources. Whereas this allows a deeper understanding of one aspect, such focused studies can support companies in establishing or improving a MC BM only to a limited extend.

The framework of three strategic capabilities proposed by Salvador et al. [16] has attracted notable attention in recent years: SSD describes the ability to identify the heterogeneities in the needs of customers and derive a suitable PO. RPD is defined as the ability to reuse or recombine given organizational and value chain resources. Finally, CN reflects the ability of customization companies to support their customers in the tasks of need specification and product customization. We will rely on this framework, since the literature review reveals that the organizational capabilities used in this framework are frequently quoted and commonly regarded as critical for customization strategies. However, although this framework provides valuable insights into organizational capabilities that have the potential to drive the success of customization BMs, some aspects of these capabilities remain unclear and require to be defined in a more detailed way. Furthermore, this framework offers only a few indications about underlying management activities and organizational resources. In order to fill these gaps, we conducted a series of expert interviews and an extensive literature review. Based on these research activities, we will extend and refine the definitions of strategic capabilities for MC in this paper. We will also present an extensive list of managerial activities and resources that underlie these capabilities.

3.1 Solution Space Development

According to the framework proposed by Salvador et al. [16], the first step toward a customization strategy is the development of a so-called solution space: High levels of customer need heterogeneity oftentimes force companies to offer a high number of product variants. Yet, offering limitless choice is economically unfeasible; thus, companies have to make a choice, clearly defining what they are going to offer and which variants will be excluded [16]. In this context, SSD describes the firm's capability to understand the individual needs of its customers and to target this heterogeneous market with a suitable selection of product variants [14]. However, due to the myriad of customer choices, this selection process becomes a rather complex task and is strongly influenced by uncertainty [41–43]. This leads to a dilemma for product managers as it becomes nearly impossible to derive a PO that is in line with the current and future market demands at the same time [44, 45]. Therefore, the respective decision-making processes should be designed to provide sufficient flexibility so that adjustments to the initially designed solution space can be made, as new information is gained [46, 47]. In order to take this aspect sufficiently into account, we propose to extend the SSD capability by differentiating between tasks that aim at defining an initial solution space before market launch and tasks that are concerned with the adaptation of an existing PO. Thus, we define the two subcategories initial and adaptive SSD in the following.

Initial Solution Space Development is defined as the sum of all product management activities that are necessary to define those variants of the new product that will be made available at market launch. While this may consist of tasks such as the elicitation of customer needs and the selection of necessary product features, SSD does not include any product design activities nor the definition of an underlying product architecture. We see two main objectives that have to be addressed by initial SSD: In a first step, potential design constraints need to be identified in order to understand which product variants could realistically be offered. In this context, "[d]esign constraints may be functions of the laws of nature, the environment in which the product will function, governmental regulations, or corporate decisions or policies" [48]. Secondly, the company has to identify the customer requirements for the respective product domain in order to identify the so-called key value attributes [33], i.e., those product attributes, along which customer needs diverge [16, 49]. For this purpose, firms have to understand the customers' idiosyncratic needs and derive a selection of product options that corresponds with the heterogeneous needs of the customers [16]. After the evaluation of all potentially feasible product variants and the identification of the key value attributes, these two sets of choice options can be synchronized to form the initial solution space.

The separation between initial SSD and adaptive SSD allows a much more detailed identification of managerial activities and organizational resources that could be applied in order to build the above-mentioned capabilities. With regard to the recognition of potential design constraints, for example, quality function deployment (QFD) proves to be a very well-documented approach for understanding technical as well as economical limitations of a product [50]. Furthermore, in order to gain a thorough understanding of all technical aspects of the product, companies could consider approaches such as patent analysis [51], reverse engineering of existing products, or the morphological box method [52]. For the identification of the individual customer needs, many different market research techniques are available. If companies are trying to gather input directly from the customers, tools such as customer interviews or surveys [53], customer focus groups [53] or conjoint analysis [54] could be applied, especially conjoint analysis seems to be a suitable methodological approach to capture the heterogeneity of customer needs concerning specific product attributes [54, 55]. However, such a direct interaction with customers may not be able to reveal latent customer needs. Therefore, firms might also want to consider methods that stimulate the creativity of customers such as innovation toolkits [32, 56] or idea contests [57]. Also, companies could try to identify such latent needs via observation techniques such as netnography [58]. Lastly, if there are already product concepts available, the customer acceptance toward these concepts could be tested with the help of physical, virtual, or rapid prototyping [59, 60] as well as test market techniques [61].

Adaptive Solution Space Development is defined as the sum of all management activities that are concerned with the assessment of the market fit of the existing solution space and potential changes to this offering. In this context, fit means the level of congruency between the existing PO and the heterogeneous customer demand within a certain product domain. If the level of fit should be insufficient, the organization needs to revise, trim, or extend the available PO [16]. If adaptations have to be made, this could be achieved either with the introduction of new choice options or with the elimination of underperforming existing variants [42, 62]. Again, we recognize two major objectives. The first objective is concerned with the solution space fit. Companies need to constantly measure some kind of fit indicator in order to be able to take any kind of corrective actions. The second central objective of adaptive SSD is the tracking of social trends or new technological developments. Such trends can be predictors of upcoming changes in a company's business environment and can thus help the firm to foresee the necessity for changing the existing PO.

In the following, this paper will suggest managerial activities that could be purposeful in the context of adaptive SSD. As indicated above, there should be a controlling mechanism for the solution space fit. One possible approach for this is the use of proxy variables. Examples for such proxies could be the tracking of customer purchase behavior, the analysis of sales data, or the monitoring of customer complaints [63]. Customers need to be enabled to transfer their experiences with the available PO to the manufacturer. Possible mechanisms for this transfer range from simple feedback forms or questionnaires [64] to regular workshops with key customers [65, 66]. Another potential activity could be the tracking of the actual customer behavior within the customization process, especially in an online context. In this case, click stream data including the number of hits, the search history, or the time spent on a certain Web site can be used for this purpose [16, 67]. Also, the sales staff plays an important role in this context, as these employees can directly interact with the customers. Thus, it is essential to link the sales personnel with other functions of the company via specific routines, so that potential changes or pitfalls can be immediately reported and communicated throughout the firm [68]. Lastly, we identify the need to monitor social trends and technological developments. For this purpose, companies need to establish corporate foresight routines to identify potential disruptions of the business environment and to turn them into business opportunities [69]. Examples of such foresight activities are trend analyses, scenarios, or technology roadmaps [70, 71].

3.2 Robust Process Design

This capability targets the issue of additional production costs that may arise from the increase in product variety [16]. In the context of such a BM, production is facing a considerably higher number of parts, processes, suppliers, retailers, and distribution channels [72]. Thus, with the increasing level of variety, the production complexity and the uncertainty in business operations are likely to increase as well [73]. In consequence, all parts of the value chain—ranging from raw material procurement to production and eventually to distribution—will be confronted with higher operational cost [14, 73]. Furthermore, increases in manufacturing cycle times and shipment lead times are to be expected [74, 75]. Thus, firms need to develop a capability that allows them to maintain the stability of manufacturing processes and the supply chain in order to be successful in implementing a HV BM [76]. One way to achieve this goal is the suggested RPD capability, which is intended "to reuse or recombine existing organizational and supply chain resources […] to deliver customized solutions with near mass-production efficiency and reliability" [16]. Subsequently, it can be stated that a successful BM for HV production is characterized by a stable, but still flexible, manufacturing process that provides a dynamic flow of products [26, 77, 78].

However, the impact of increasing product variety on production cost cannot only be mitigated by reconfiguring the manufacturing process and bringing a higher degree of flexibility to the production, but product development has to be considered as well. This paper supports the idea that the integration of certain activities during the development of new products can lead to an improvement in manufacturing process stability. Thus, we suggest differentiating between two strategic capabilities in this context: RPD and "Product Design for Process Robustness".

Robust Process Design. With regard to RPD, we completely follow the suggestions of Salvador et al. [16] and define it as the capability that aims to achieve the necessary robustness of manufacturing processes with respect to the heterogeneity of orders, by determining a suitable production system architecture and respective logistics that facilitate an efficient and flexible production. As we do not differ from the original definition in this case, the identification of relevant managerial activities is less complex: Literature suggests a number of different activities or organizational resources that can be applied to reduce or even avoid the additional costs of variety in manufacturing. Some of these methods will be presented in the following.

A possible starting point for increasing the robustness of the manufacturing process for HV POs is the implementation of process modularity [16]. This can be put to practice by considering manufacturing and supply chain processes as segments that are necessary in order to realize specific product variants [76]. In such a modular setting, firms can serve individual customer choices by appropriately recombining the process segments [79]. Also, companies could consider the concept of postponement or delayed product differentiation in manufacturing or distribution logistics in order to increase process robustness. Delayed product differentiation reorganizes the supply chain into a generic preproduction phase and a customer-specific phase, in which a product is customized to the customers' preferences [80–82]. Beyond reorganizations of the manufacturing process itself, there are many new technologies available that can help to increase the process flexibility: Computer-integrated manufacturing [14, 83], flexible automation [26, 79, 84], robotics [85, 86], or the use of rapid manufacturing technologies such as 3D printing [87] are some of the examples that are discussed in the literature. Besides these flexible technologies, companies need to train their employees for dealing with novel task, so that they can be assigned flexibly in the manufacturing processes [16, 88]. Furthermore, supply chain logistics need to be reconsidered as well: Just-in-time and just-in-sequence logistics enable a lean logistic concept that allows prompt response times, even in case of unexpected changes [42, 89]. Lastly, the robustness and flexibility of manufacturing processes should already be considered during the development of new processes. This could be achieved by an interdisciplinary development approach that respects the requirements and concerns of all affected departments [90].

Product Design for Process Robustness. Whereas the description of RPD provided above strongly follows the original framework of Salvador et al. [16], we extend this framework with a new capability, namely "product design for process robustness". This extension builds on the idea that the use of certain activities during new product development can foster the robustness of the resulting manufacturing processes. Similarly, Vickery et al. [91] claim that a close collaboration of product design and development, marketing, and manufacturing is needed in order to realize sufficient product flexibility. Subsequently, we formulate the following definition: Product design for process robustness aims to achieve the necessary robustness of manufacturing processes with respect to the heterogeneity of ordered product variants, by determining a product architecture that facilitates an efficient and flexible production.

The operational realization of this capability can manifest itself in several different activities and organizational resources: Firstly and most importantly, it has to be decided whether each product variant is developed separately, or whether the new product development process is carried out jointly for a variety of products. Research shows that the approach of developing products one by one oftentimes leads to a proliferation of products and parts, as issues of commonality and standardization do not receive sufficient consideration [19, 92]. Thus, literature recommends a platform-based development approach that builds on an overall logical structure for "generating a family of products by providing a generic umbrella to capture and utilize commonality [, while designing] an entire class of products [...] based on individually customized requirements within a coherent framework" [93]. If companies decide to follow this approach and intend to develop a full PO in a joint development process, the definition of the product architecture has a major impact on the manufacturability of the future product variants [94]. The selection of a specific product architecture—e.g., integrated, modular, or parametric—determines the "mechanism" that is used to reach process flexibility [95]. Thus, companies have to decide rather early, which product architecture and which realization mechanism are best suited for the production of the intended solution space. Lastly, cross-functional collaboration plays an important role in developing new products: In order to guarantee manufacturability, all relevant functional areas of the company should be integrated in the development process [96]. Such a use of cross-functional teams [90, 97] or concurrent engineering methodology [19] allows the firm to integrate the specific requirements of ramp-up management or manufacturing at an early point of time [98, 99].

3.3 Choice Navigation

According to Salvador et al.'s [16] framework, firms pursuing a customization strategy need to develop and implement a CN capability. From an economic point of view, CN addresses the question how customers' non-monetary costs associated with the transfer of information between firms and customers can be kept as low as possible, while the overall value for customers can be increased at the same time. This captures one important aspect of the necessary information transfer and interaction between a company and its customers. But, a description of this capability that takes all relevant aspects into account, in our opinion, requires a broader definition. Thus, we define interaction competence (IC) as a firms' ability to master all aspects and activities related to the necessary information transfer during the customization process. Further, we define two subdimensions of IC, namely external IC and internal IC.

External Interaction Competence refers to the ability of a company to efficiently support customers in identifying their needs and creating their own solutions, such that choice complexity is minimized and/or enjoyment of the search/configuration process is maximized. As mentioned above, customizing products according to the specific needs of each individual customer requires additional information to be transferred between firms and their customers [6, 29, 100]. This information transfer usually takes place in the form of an interactive process, including the customer and the company. The aim of these processes is to identify customers' demands and to translate them into a product that is feasible within given production possibilities [6, 14]. For customers and companies, interaction processes are associated with additional transaction costs [18, 30, 101]. For customers, the amount of these non-monetary costs depends on how they evaluate the interaction process in terms of the effort and the perceived benefits arising from it. Customer effort is caused by the need to actively take part in the interaction process. This can lead to dissatisfaction or may even cause the customer to not buy any product at all [28]. Therefore, companies need to apply certain activities in order to support customers in identifying suitable solutions, while minimizing complexity and burden of choice [16]. Additionally, the literature on customization offerings in B2C markets indicates that hedonic benefits can be associated with interaction processes: Customers expect to have a more enjoyable shopping experience while creating their unique solution [12, 64, 101–103]. Here, hedonic value can be induced by creative achievement [12] or a feeling of having created something [102]. Since hedonic value is positively related to customers' willingness to pay for customized products [64], companies are asked to design their interaction process accordingly.

The following managerial activities and organizational resources are identified as drivers of external IC: In order to reduce the variety-induced complexity, companies should implement an easily understandable [cf. 16, 18, 28, 30, 104, 105] and well-structured interaction process [12, 104, 105]. Provision of technological devices, such as augmented reality devices or 3D visualizers, can help customers to get a better understanding of their own needs [106, 107] and thus can also reduce uncertainties during the customization process. In addition, it is suggested to provide customers with more information about the product and the available customization options during the process. Such information is valuable for the customers, since they cannot test or see the product before it will be manufactured [28, 102, 107]. Randall et al. [104] note that different sales channels or differently designed interaction processes provide the possibility to address different types of consumers more precisely. For online customization offerings, it is recommended to implement configuration or software tools to interact and codesign with customers [cf. 14, 16, 104, 105]. Other studies suggest complementing online-based customization offerings with recommendation systems [108]. Also, Dellaert and Dabholkar [107] show that interaction with trained sales personnel makes online customization offerings less complex and more enjoyable for customers. Similar benefits may result from interacting with sales representatives in classical retail stores. They can help customers to better understand product characteristics and to match these with their own needs more precisely [109]. Thus, especially in offline environments, an adequate support for customers requires a well-trained sales staff, that possesses all necessary competencies [18, 104].

Internal Interaction Competence. A prerequisite for a successful realization of interaction processes is that all related information can be handled in an efficient way [23]. We define this capability as internal IC, which represents a companies' ability to efficiently handle the flow of all customer-order-specific information. On the one hand, internal IC needs to be realized, so that customers can be provided with distinct product-related information during interaction processes. The importance of providing real-time feedback to customers on product configurations has been stressed by different studies [6, 16, 105–107, 110–112]. Providing product-related information helps to increase transparency of the interaction process and reduces the risk that customers experience complexity and uncertainty [18, 30]. Furthermore, it increases satisfaction and demand for customized products [111]. On the other hand, internal IC incorporates a companies' ability to process customer and order-specific information in order to increase the efficiency of internal operations.

In the following, we provide management activities that may help companies to strengthen their internal IC. Key enabler for the efficient provision and processing of information are information systems, information technologies, and configuration systems [cf. 14]. These systems allow serving customers with product-related information during the customization process in real time [111, 112]. This includes the provision of information for a customer-specific product in regard to feasibility [106], technical characteristics and virtual models [106, 111, 112], price and costs [6, 107, 112], or delivery dates [106]. However, these systems also allow for an automatic generation of information about each single product variant, thereby increasing the efficiency of internal operations. For example, this includes the preparation of bills of materials [112–114] or manufacturing-related information [112]. Complementarily, the availability of technologies such as measurement devices [14, 115–117] and appropriate (technical) sales support systems [14, 102, 105, 118] can help to collect, process, and use information during the interaction process and thereby may lead to an increase in process efficiency.

4 Conclusion

This paper provides research on strategic capabilities for companies that are facing rather heterogeneous market conditions and that are required to provide HV POs. In particular, our research focuses on the role of underlying activities and organizational resources that—in combination—are the building blocks for the relevant strategic capabilities. In this context, our paper contributes mainly in two ways to the existing research on HV production environments: Firstly, we extend and refine the definitions of capabilities for BMs related to HV production strategies. As a starting point, our research uses the capabilities framework for MC proposed by Salvador et al. [16], which describes three rather broadly defined strategic capabilities. Our study refines this set of capabilities by defining two subcategories for each of the three original capabilities and thus enables a detailed discussion of potentially relevant activities and organizational resources. Secondly, we derive an extensive list of managerial activities and organizational resources that could serve as individual building blocks for the above-mentioned strategic capabilities (see Appendix for a full list of activities). Subsequently, our research provides practitioners with an overview of activities that can be implemented in order to strengthen a company's ability to provide a HV PO.

Naturally, the research approach that has been applied for authoring this paper is not free of limitations. Two major limitations of this paper will be considered in the following. Firstly, the results of this study are based on a literature review and a relatively low number of expert interviews, only. In order to strengthen the validation of the theory-based proposition of the paper, more empirical evidence in the form of additional expert interviews might be needed. On the other hand, however, existing research shows that the amount of eight interviews might be sufficient [119, 120]. Nevertheless, additional expert interviews could provide further insights. Secondly, this study relies completely on qualitative data. Therefore, it would be interesting to validate the results with quantitative empirical data. Such data could be collected via a large-scale survey of companies that offer HV POs for markets that are characterized by high customer demand heterogeneity.

Our research results show that there is still more research needed in this field. For this purpose, two potential gaps that require further research will be highlighted in the following. Firstly, the results of this study could be extended with regard to the managerial implications. Further research needs to support practitioners in applying the identified managerial activities and organizational resources by prioritizing the suggested approaches. A large-scale survey among manufacturers of HV POs could indicate which activities or routines have the strongest impact on the respective strategic capabilities. Secondly, future research could try to investigate the impact that individual managerial activities or routines suggested in this paper have on the overall firm performance.

Appendix

Table 1

Table 1 Activities and organizational resources for the strategic capabilities of MC

Solution space development	
Initial solution space development	Adaptive solution space development
• Quality function deployment	• Feedback system for customers
• Conjoint analysis	• Meetings with key customers
• Customer focus group/interviews/surveys	• Regularly contact with the customers
• Lead user method	• Data mining
• Innovation toolkits	• Interest groups
• Ethnography/netnography	• Trend analysis
• Idea contests	• Routines/processes for sales/service staff to report changes
• Physical prototypes	• Routines/processes for our sales/service staff to report pitfalls
• Rapid prototyping for customer feedback	• Track the customers' behavior
• Virtual prototypes for customer acceptance	• Analyze customer complaint
• Auctioning mechanisms	• Analyze past sales data
• Test markets	• Analyze customer behavior in the configuration process

(continued)

Table 1 (continued)

Solution space development	
• Principles of design of experience (DOE)	• Interview former customers
• Benchmarking	• Contact the suppliers
• Reverse engineering	
• Morphological box approach	
• Brainstorming	
• Patent/portfolio analysis	
Robust process design	
Product design for process robustness	Process design for process robustness
• Interdisciplinary teams	• Interdisciplinary teams
• concurrent engineering	• concurrent engineering
• DFM/DFA	• Simulation techniques
• FMEA	• FMEA
• Modular product architectures	• Pull production
• Integrated product architectures	• Form/time postponement
• Parametric design	• SCM logistics for unexpected changes
• Manufacturing requirements	• JIT/JIS logistics
• Requirements of production ramp up	• CIM/flexible automation/robotics
• Product platform	• Rapid manufacturing technology
	• Reconfigured in a modular way
	• Employees can be assigned flexibly
	• Train employees to deal with novel tasks
	• High degree of flow production
Choice navigation	
External interaction competence	Internal interaction competence
• Recommendation system	• Option to track the status of their order
• Configurator/software tool	• CAD/CAM data
• Cocreation	• Real-time feedback
• Realistic visualizations	• Cost structure
• Augmented reality devices	• Product identity code
• Extensive information	• Bill of materials
• Trained employees	• Measurement devices
• Joyful experience	• Technical support systems
• Well-structured process	
• Easily understandable process	
• Multiple customization channels	

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The Impact of Mass Customization on the Artist's Paradigm in the Twenty-First Century

Donald M. Rattner

Abstract The image of the artist as a solitary figure who creates art that is autonomous, physically inviolable and subject to fluctuating prices has remained relatively constant since the gallery system was established in the mid-nineteenth century. The advent of computer-aided manufacturing and mass customization now threatens to replace or augment that paradigm with a more democratic alternative. This talk examines the potential form the new paradigm may take and presents several examples of artists using mass custom technologies to create contemporary art.

Keywords Art gallery · Art market · Contemporary art · Customizable art · Mass customization · Modular · Modular art

The generalized perception of the contemporary artist as a creative figure in present-day culture, as well as the workings of the fine art market in which the artist operates, have remained relatively true to their historical origins in the nineteenth century [1] despite the upheavals experienced in other markets from the effects of computerization. This condition raises two questions: first, how has the persona of the contemporary artist so far managed to resist the wave of change that has profoundly altered so many disciplines and markets, and second, what impact might mass customization and other digital production technologies have on this persona and, by extension, the art market as a whole should they come to have an impact in the future?

Addressing this latter question will necessarily be the focus of this paper, but to explain the nature of the shift in the artist's paradigm that will be proposed during the discussion, it is first necessary to describe the state of that persona as it currently exists. Perhaps, no better single image encapsulates this persona than a 1966 photograph taken of the artist Ad Reinhardt (1913–1967) working in his New

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Fig. 1 Ad Reinhardt in his studio (*source* John Loengard/Time & Life Pictures, via Getty Images 1966)

York studio (Fig. 1) [2]. Though it was taken nearly half a century ago, this photograph remains a superb snapshot of what it means to be an artist in the twenty-first century—in particular, how the artist works, what their relationship is to the work of art and to those who buy art, how the work of art relates to its context, and how art is sold. Each of these issues is important insofar as it is the contention of this paper that they will all be substantially transformed in the coming years as a result of advances in mass customization.

Looking at the photograph, one's first impression is likely to be of the artist working in solitude. That solitude is most obviously conveyed by the fact that there is no one else in the studio. Even the photographer is rendered effectively absent by being positioned high up in the space, perhaps perched on a ladder so as to obtain a bird's eye view that suggests an otherworldly, omniscient vantage point not normally associated with everyday human perspective. The extensive foreground in the image occupied by a large expanse of an empty wood floor adds to the sense of quiet emptiness. Even the city glimpsed through the plate glass windows feels distant and quiet, perhaps because of the barrier set up between artist and outside world that the closed windows imply, or the somewhat clouded, low contrast effect that lays over the buildings and streetscape, in contrast to the strong lights and darks visible on the interior side. This carefully orchestrated image of solitude and singular focus on the work of art serves to reinforce the image of the contemporary artist as an autonomous, heroic, self-enveloped genius whose creativity springs entirely from within.

That introspective quality is further reinforced by the lack of any figurative models or other points of references among the room's furnishings and paraphernalia, and by the artist's indifference to the city outside. These are not arbitrary qualities, but signifiers of the artist's persona, for the lack of connection to external realities is aesthetically consistent with the abstract qualities of the canvas the artist is painting. It is in fact one of numerous canvases within Reinhardt's Black Painting series of the 1960s. These are works which at first glance look to be simply canvases painted black, but on closer inspection turn out to be composed of areas in variable shades of black. Being so nearly devoid of content, the black paintings can be said to have no context, no connection to the world around it. For that reason once they were done, they could be hung almost anywhere, and for that matter, could be placed in almost any orientation since they lack a discernible top and bottom.

One might nevertheless argue that contemporary art of the sort embodied by the black paintings do in fact have a context, or at least an intermediate one, and that is the white cube of the contemporary art gallery. For as was most likely the case, this piece was being made on speculation by Reinhardt for sale to an unknown buyer. Once completed, it would have been consigned to his dealer who would have put it on view in his or her gallery. A collector would eventually have bought it at something near the asking price after negotiation and then installed it in his or her private residence or place of business. Over time, the piece would likely have been resold and moved multiple times. If the artist achieved increasing recognition for his work, as this one was, the price of the artwork would have risen over time as it was re-sold, in part because supply would inevitably be limited by the finite output an artist could achieve in a lifetime.

At no point in its history would anyone have thought to alter this work of art. Not only would that have been considered amoral and a violation of a silent pact entered into with the artist, but anyone doing so would have been financially foolhardy, since it would have eliminated almost any chance of the work retaining its monetary value. That monetary value, incidentally, would have been entirely subject to the whims and judgment of the market, there being no factual or tangible basis for calculating its worth.

Returning to the photograph once more, it cannot have escaped notice that the artist is creating the work of art by hand, with a paint brush, much as his forebears did in the Renaissance, antiquity and perhaps even in the caves of Lascaux 40,000 years ago. At least within the framework of physical production, this very modern artist is creating a hand-crafted custom work of art using manual techniques that have typified artistic production for centuries and even millennia. So while conceptually much of contemporary art speaks of an entirely modern and unprecedented set of ideas about the world, from a production standpoint, most contemporary artists remain firmly grounded in the historical spectrum, as can be shown from even the most cursory review of the current art market.

Contemporary art, then, is a curious mix of both entirely modern paradigms of the artist as a singular figure creating unique pieces that are delivered to the market in a fully completed state, devoid of context, and which are to remain unaltered in perpetuity, and an historical production model which is largely manual in nature and which derives value in part from the scarcity that ineluctably derives from its origins in the individual artist.

For these reasons, it appears that fine art would be ripe for the kind of disruption brought on by the advent of computerization that has transformed so many other fields of human activity. Moreover, mass customization, insofar as it involves the production of tangible goods by means of a visual interface, and since oftentimes those goods require creative input on the part of the user to be realized, would appear to be a particularly suitable mechanism for effecting change in the fine art market.

What would a recast artistic paradigm look like if mass customization were brought to bear on the production of art? To begin to answer this question, one might compare and contrast the salient characteristics of the artistic paradigm as it was dissected in the Reinhardt image with how such characteristics might be transformed in a post-industrial, digitally driven era.

For example, consider that most fundamental precept of the contemporary artist, namely, that the artist is a lone figure who creates finished work without direct input from others. In a mass customization environment, the artist neither operates alone and nor produces completed work; rather, he or she is joined by a co-creator, a collaborator who will take up where the artist leaves off to finalize the work. This constitutes a fundamental sea change in how to think about the artist's relationship to the work of art. No longer does the artist possess a proprietary, exclusive, and top-down right to ownership of the work of art; in a mass customization framework, art is a joint venture involving multiple parties, each playing a role in the creative process. To be sure, the artist remains critical in his or her initial conception of the idea behind the work of art, but rather than executing the work from start to finish, the artist sets up a system or platform that others can use to generate their own iterations, which can then be shared across communities. Meanwhile, the collector of old is transformed from a passive observer and consumer of art to an active participant in its realization. The consequence of this approach is to democratize art, to make it more consistent with the horizontal, crowd sourcing, and open innovation practices of the twenty-first century than the vertically stratified social paradigms of the past.

Another change involves the means of production. No more does the artist toil in an artisanal culture of hand-crafted objects, in its place comes post-industrial manufacturing. Rather than wield a brush, the artist writes code to translate his or her vision of the artwork to be into transmittable form. Rather than being the direct output of the artist's hand, the work of art is fabricated by robotically controlled machinery following the commands of digitally transmitted computer files. Rather than making art only during the artist's waking hours and in his or her studio, now, art can be made anytime and almost anywhere.

There are a number of advantages in changing the means of production to a mass-customized model. For one, the scarcity principle which is so fundamental to valuing traditional art is replaced by the abundance principle. The scarcity principle follows classic laws of supply and demand in positing that prices will rise when a product's supply is constrained, all other things being equal. In the case of traditionally produced art, an artist's supply of work is naturally limited by how much he or she can produce in a finite lifetime. For increasingly successful artists, that invariably means that prices become inflated as demand increases, which means that fewer and fewer people can afford them. And once the artist passes away, a permanently limited supply puts even further pressure on price affordability, provided the artist's reputation remains intact. The same holds true when considering the individual work of art, at least those manually produced in non-replicable media. Being singular and unique, the value of each piece is potentially unlimited since it is irreplaceable.

Mass-customized art, on the other hand, has no built-in limitations on supply and therefore is less susceptible to diminished affordability as a result of increased demand. Nor do prices spike when the artist passes away and supply is cut off, since the files live on indefinitely. The paradox of popularity evident in the traditional gallery model gives way to perpetual democratic accessibility.

A similar change takes place with regard to price structure. In the traditional gallery model, pricing is speculative and negotiable, which is to say, the price of a work of art is whatever someone is willing to pay for it at any given moment. It is almost entirely based on market perception, since there is no direct correlation between the time and materials initially required to produce the piece and it is agreed on selling price. And of course, because it is based on intangibles, no one really knows whether the price will go up or down in the future.

Mass-customized art, by contrast, works on a computed pricing model, meaning that the cost of fabricating the piece can be calculated objectively. Profit and overhead as a percentage of costs can be added on top of the cost of goods, making the price a potentially transparent and objective figure. Being industrially produced, it is not subject to price negotiation or wide market swings. And that is a good thing, because the art market is generally one of the least rational places to invest one's money, not only because traditional art is so subjectively speculative, but also because the entire gallery system is extremely non-transparent and unequal in its distribution of information. In some cases, asking prices are not even published, and rarely is the actual purchase price of first-time sales divulged. With mass-customized art, the price is up front and the same for all.

The clandestine nature of the contemporary gallery system is not accidental, of course. Part of the mystique that clouds its inner workings is devised intentionally in order to preserve what has been called the "aura" of the work of art. This aura helps to elevate the perceived value of the artwork by distinguishing it from the everyday, commonplace character of other types of tangible goods.

Compared to traditional fine art, mass-customized art is unabashedly quotidian, commonplace even. Born in the post-industrial factory and infinitely replicable, it can have no pretensions to sacredness or cultural apotheosis. It can almost never be worth more or less than what it starts off being worth. Hence, a work of mass-customized art needs only be insured for its material replacement value, since that would be the cost to restore it to original condition if lost or damaged.

None of these remarks are intended to give the impression that the contemporary art market is a nefarious operation and that mass customization is a white knight that will cure its alleged shortcomings. Nor should it be overlooked that others have offered their own proposals for modifying the artist's paradigm over the years. For example, in 1959, a Swiss artist named Daniel Spoerri founded a groundbreaking publishing entity known as Edition MAT, or Multiplication d'Art Transformable [3]. This now somewhat forgotten group promoted the art multiple as a solution to the problems of affordability and exclusionary pricing associated with unique works of art. It also advanced two other characteristics that have some connection to this discussion. One was that works of art need not be static and immobile, as they traditionally were, but could incorporate movement and mutability. The second was that contemporary art could be participatory, interactive, and open-ended, rather than something to be delivered finished by the artist to the collector or observer, never to be altered again for fear of compromising value.

Yaakov Agam's transformable painting and sculpture series is a case in point [4]. In these works dating from the 1950s on, some of which were issued by Edition MAT, the artist invites the viewer to not merely view the work of art passively, but to physically engage with it by re-positioning two- and three-dimensional pieces devised by the artist within a frame or assembly. Agam's work thus presages a key characteristic of mass customization as it pertains to the production of objects, namely, that of interactive customer co-creation. Substitute the artist for the company offering mass-customized art, and the viewer or co-artist for the customer, and Agam's transformable works lay a pathway to mass-customized art in the twenty-first century. Where they differ is largely in the means of production. Agam's works were almost entirely hand-made; today, mass-customized art is by definition fabricated by computer controlled machinery, absent of the human hand, at least in its initial stage.

The computer plays a critical role in the interaction between the co-creator and the mass-customized work of art (Fig. 2). Thanks to the use of a configurator, the co-creator can participate in devising both the form and content of the mass-customized work of art. The e-commerce venture Juicy Canvas, to take one example, offers the buyer a series of graphic templates with which to begin the customization process [5]. A buyer can then rotate, re-size, re-orient, colorize, and add text on the canvas before proceeding to checkout.

While Juicy Canvas' attempt to offer customizable art is commendable, it nonetheless fails to realize the full potential of mass customization, starting as it does with the kind of conventional illustration art that would normally be framed and hung as is. Little about these templates suggests that they were initially conceived with the intent of being subsequently manipulated by a co-creator

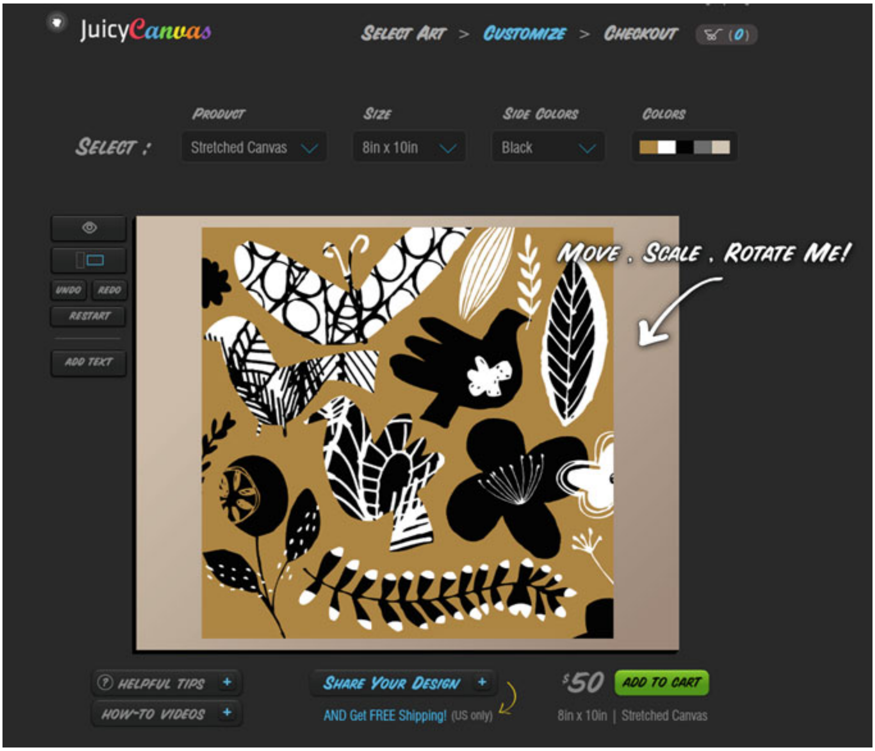

Fig. 2 Juicy Canvas configurator (*source* [5])

within the framework of a configurator. Somewhat more promising is work coming out of Ixxi, an Amsterdam-based company [6]. Ixxi's product is a modular system of interconnected printed cards hung on a wall in a regular grid. The images printed on the cards can be uploaded by the user and can either be printed one to a card or the entire grid can represent a single image. Ixxi also offers a collection of pre-designed cards in both formats. Grids range in size and are rectangular or square in overall proportions, each card being a square.

The cards are delivered stacked in a box and with all the necessary connecting pieces and hanging supplies. The buyer can then choose how to actually arrange the cards before mounting the assembly on a wall.

Ixxi is especially germane to the discussion of mass-customizable art because it is modular. Modularity, as is often noted, goes hand in glove with mass customization from both a production and conceptual standpoint. By its very nature, a product designed in a modular framework lends itself to being creatively manipulated by the addition, subtraction, or reconfiguration of its component modules. In the case of Ixxi, individual cards can be configured within the grid any way the user chooses to form different patterns or assume different overall shapes. A user

Fig. 3 Five modular units at the Storm King Art Center, by Sol LeWitt, 1974. (*source* John Menard via Flickr, http://www.flickr.com)

can also add or take away modules to suit their needs or preferences, or perhaps external exigencies, such as in the case where the piece has to be moved.

Historically, the idea and practice of modular art is not new. In the 1950s, artists such as Norman Carlberg and Erwin Hauer were known as modular constructivists for their work combining repetitive elements of an architectural character [7]. But it was in the 1960s that modular art really began to coalesce in a coherent body of work. Perhaps, best known then and later was Sol LeWitt, a prolific inventor of abstract art based on repetitive units (Fig. 3).

LeWitt is a central figure in a discussion of mass-customized art in several respects. First, he embodies the idea that modular art originates in industrialism. That is to say that the concept of a standardized unit infers industrial production, rather than artisanal craft, because in order to be truly standardized to ensure exact fit with adjacent units, the unit must be made exactly the same each time. It is the factory, not the workshop, that can ensure this level of precision. LeWitt, as is well known, often did not actually execute his own work, but provided written or graphic instructions for others to do so, thus distancing himself personally from the physical work of art, in contrast to the direct connection of the artist and his work that was represented in the image of Ad Reinhardt discussed earlier. Technically, a LeWitt piece could be executed any time, anywhere and by any one, making it conceptually at least an industrially fabricated product. Mass-customized products are by definition industrially made, and with the advent of digitized production, even more precise than was possible in the first Industrial Revolution and therefore a consummation of the industrial ideal. Modular art and mass customization are, once again, simply natural bedfellows.

Another notable quality of LeWitt is his proclivity for placing his work in architectural contexts. Many of his pieces were conceived for specific interior environments, and in some cases, he executed semi-architectural three-dimensional structures evocative of building forms. Unlike the kind of non-contextual work, we saw being produced in the Reinhardt image, LeWitt's pieces often connected to their surroundings in very direct ways. This underscores still another shift in the artist's paradigm in the age of mass customization, namely, that mass-customized art and modular mass-customized art in particular are potentially site-specific, able to be designed and fabricated to harmonize with their actual surroundings. Moreover, in the case of modular art, a piece can be disassembled and re-configured, expanded, or diminished to suit a new location if it is ever moved, a degree of flexibility that the immutable canvas by Reinhardt never had nor aspired to.

Still, in certain respects, LeWitt shares Reinhardt's allegiance to the traditional artist's paradigm. Like Reinhardt's canvas, his works are also considered inviolable, precious objects whose price fluctuates according to the market. Any physical alteration inflicted on them would be regarded as a compromise of their artistic integrity and their potential market value. At the end of the day, LeWitt's embrace of modularity is therefore more thematic than actual.

In contrast to LeWitt, mass-customized modular art is post-industrially manufactured, affordable, user friendly, generative and needs only the input of a co-creator to be realized. It is composed of repetitive and standardized units that, paradoxically, can form unique compositions, making them a kind of distant relative to the hand-crafted creations produced by traditional artists. No longer a solitary heroic figure and the sole author of the work, the artist's persona is now that of a collaborator and an instigator.

To date, only a handful of contemporary artists and designers have begun to investigate this line of inquiry. Among them is the Swedish designer Mia Cullin [8], who has created a series of modular tapestries out of wool felt as well as from industrial materials (Fig. 4). Clearly inspired by Cullin, the New York firm Studio for A.R.T. and Architecture, which is headed by the author, developed its own line of modular felt tapestries [9]. Produced on-demand, available in several different shapes and in an array of colors, the modules are made of wool felt laser cut from files uploaded over the Internet and then shipped to the customer in sheets. Customers piece the modules together to form the tapestry, which can be composed in form and color to suit its surroundings.

Studio has also explored modular mass-customized art using more solid materials, such as MDF veneers and acrylic. Their sculptural wall assemblies combine both materials, as well as felt, in a series of variously shaped modular systems that join together by connecting cross-pieces (Fig. 5). Here, one observes modularity's capacity for configuring site-specific art; note how the piece fits around the various openings and steps down with the ceiling to nestle comfortably and deliberately into its environment, unlike a traditional rectangular or fixed piece that would have been superimposed on the backdrop with little inflection toward its surroundings.

Fig. 4 Flake, by Mia Cullin (*source* [8])

Fig. 5 Wall art installation by Studio for A.R.T. and Architecture, 2010 (*source* Timothy Bell)

As these early efforts attest, the application of mass customization practices to the production and sale of fine art is at an incipient stage. Significant opportunities lie ahead for artists, designers, and entrepreneurs wanting to further explore the new artistic paradigm of mass customization.

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The Impact of the Arrangement of User Interface Elements on Customer Satisfaction in the Configuration Process

Paul Blazek and Klaus Pilsl

Abstract Configuration systems are important drivers for the concept of mass customization. One of the main challenges when conceptualizing, designing, and implementing such a configuration system is the creation of an appropriate user interface. The recent literature covers a lot of different findings, which criteria a B2C product configurator should fulfill to offer the customer an optimal customization process. A case study by Streichsbier et al. (The Influence of De-Facto Standards on Users dealing with B2C Configuration Systems, Taipei 2010) identified de-facto standards according to the position and availability of certain Web elements within the user interface of configurators of the automobile, apparel, and electronic industries. As the identified standards vary within the industries, for the following study only the apparel industry, strictly speaking T-shirt configurators are considered. The empirical aim of the present study, based on user observation, is to find out whether or not the structure of a configurator's user interface has an influence on the customers' process satisfaction.

Keywords Configuration system · User interface · User testing · Mass customization · Web standards

1 Introduction

A well-designed, usable interface is considered as an essential criterion for the success of interactive solutions [1]. Meanwhile, a lot of literature addresses the importance of user interfaces and formulates guidelines for the preparation of such systems [2]. The main goal of a configurator is to enable the user to create the

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desired product [3]. Therefore, a configuration system should be as user-friendly as possible to guarantee a proper human computer relationship [4].

Over the years, diverse guidelines and conventions of user interface design were developed. Consequentially, users build up habits and expectations toward a Web-based user interface [5]. It has already been empirically proved that users have expectations concerning the location of relevant Web elements of e-commerce shops like the login button, the shopping cart or the help button [6].

A case study by Streichsbier et al. [7] detects such standards within the automobile, apparel, and electronic industry. Nevertheless, they suggest proving if the identified standards accompany with user experiences and expectations [7]. A market study published by the European Commission [8] points out that mass customization in the fashion industry is of growing importance: “Customized clothes has become a niche market and is expected to be worth EUR 27.2 billion by 2020, corresponding to 5 % of the global clothing industry.” Therefore, the aim of the conducted study was to figure out whether or not structural standards of configurators in the apparel industry have any influence on the customer’s process satisfaction. By using the technology of Combeenation [9], four T-shirt configurators have been created and compared by conducting a user observation.

2 The Role of User Interface Design for Web-Based Product Configurators

2.1 The Need for a Usable Configuration System

One of the fundamental capabilities of the mass customization approach is to establish the right interaction environment for customers, so they can create products according to their needs, namely choice navigation. It is crucial for any configurator to support the customers in identifying their needs and at the same time to minimize complexity for the user [10]. So the user interface of Web-based configurators is a key success criterion for the customer’s satisfaction, as the configurator is the only and most important touching point between the customer and the manufacturer [11]. Dockenfuß [12] emphasizes the importance of a well-designed configurator with the statement “a user who creates his own products expects a graphic design that is easy to interpret and use, and employs a familiar terminology.”

Rogoll and Piller [13] defined three criteria from the user’s point of view, which a configuration system should fulfill: (**a**) **Risk reduction and trust building**: A configuration system should build up a user’s confidence and show competence. (**b**) **Usability**: Operability and self-explanation, orientation, individual access on information, loading time, and support. (**c**) **Visualization**: As customers do not have any chance to judge the real, physical product, it is essential to provide the customer a real feeling of the product. Another meaningful attribute is the fun factor a configuration system should deliver, as it leads to higher customer satisfaction and willingness to pay [14].

2.2 Definition and Advantages of User Interface Standards

According to Nielsen and Loranger [15], the existence of de-facto standards is given, if a Web element is designed in the same way on 80 % and more Web sites. Users expect these elements to function in the same way. Arguments against and for the usage of Web standards can be found in many research publications. Nielsen and Loranger [15] express the potential of standards quite radical "the more you stay departed from using standards the more likely appears the danger that you confuse or even lose your customers." Since standards provide a secure feeling by having a Web site under control, they increase customer satisfaction [15]. Adkisson [16] defines reduced development costs and high usability as core arguments for standards.

Advantages for the users are higher usability, less training, acceptance of the system and higher satisfaction, whereas saving time and work, simplifying quality control, reducing training time are declared as advantages for developers of such systems [17].

Contrariwise, it is indicated that Web standards may cause that companies lack in individuality and are not able to create their own solutions [16]. Furthermore, it is criticized that Web conventions and Web standards are not up to date, which is why practice-orientated research is getting more important [18].

2.3 Structural Standards for Web-Based B2C Product Configurations

According to several studies, Bernard [6] justifies the relevance of right located Web elements within an online shop. 2001 Bernard has observed 302 subjects concerning their expectation of the position of well-known Web elements in e-commerce Web sites. The results confirm that customers have developed certain prospects in terms of the structure of e-commerce sites [6]. In 2006, Shaikh et al. [19] have conducted a similar analysis to find out whether the expectations of users have changed, caused by new technological evolution, and increased Internet usage since 2001. The results of Shaikh and Lenz's study corroborate Bernard's findings from 2001.

Referring to Bernard's [6] results, Streichsbier et al. [7] have identified certain standards and guidelines in the automobile, electronic and apparel industries regarding to the placement of Web-objects within the user interface such as buttons, toolboxes, and text fields. As within the apparel industry products vary a lot, the sample has been subdivided into configurators for T-shirts and shirts.

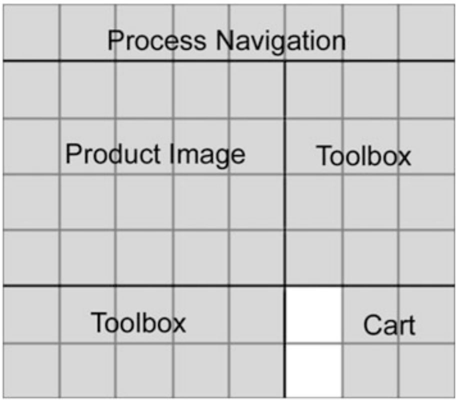

Fig. 1 Structure of a T-shirt configurator based on identified standards [7]

A total number of 30 T-shirt configurators have been observed. In the following, the identified standards for T-shirt configurators are listed [7]:

- 100 % of the observed configurators use real product images.
- 90 % support customers with a visual feedback showing choices and alterations made and 83 % represent several perspectives and viewing points of the product image.
- The average product image size is 315 × 337 px.
- 80 % show and update the price during the configuration process.
- 77 % of the configuration takes place on a single screen and do not lead the user through a configuration process.**Structure of T-shirts Configurators**. Figure 1 depicts the statistical likeliness of the position of relevant elements in a structural frame of T-shirt configurators.

3 Empirical Analysis

3.1 Research Aims

Rogoll and Piller [13] stress the need of testing user requirements when designing configurators. Streichsbier et al. [7] also recommend checking the identified standards, described in 2.3, on the basis of user testing. The analysis aims on figuring out whether or not standards concerning the structure of a configurator as the position of Web elements (e.g., toolbox, product image, and process navigation bar) have any influence on the user's process satisfaction. To exclude confounding factors like different designs or different design options, this study was conducted with the same configurator in different variations so that only the structure varies but not the tool or the design options itself.

3.2 Method and Setting

The empirical focus is put on a special kind of user observation. For the following qualitative analysis, 6 users have been observed while dealing with four T-shirt configurators. All subjects chosen for the usability test are familiar with online shops and have already purchased products online. According to Nielsen [20], the amount of 5 users for usability testing is sufficient as 5 users can detect already 85 % of the usability problems within the first testing round.

The method used for the study is a “thinking aloud” approach. During testing, the users are asked to speak out loud all thoughts that come to their mind while using the configurator. The observer can understand the user’s interaction with the configurator as intentions become visible. In that way, a holistic emotional and rational behavioral pattern of the user while operating the configurator is to be researched. Problems of the interface can easily be discovered because the observer can see the difference between what the user is thinking and actually doing [21].

All subjects have been asked to fulfill the following task with all four T-shirt configurators: “Create a polo T-shirt in size medium with an image of an ice and your name on it.”

To avoid any interference concerning process satisfaction and duration, the configurators have been presented in a different order. During the observation, the listed aspects have been considered:

- **Handling**: Is the structure of the configurator clear and easy to use?
- **Orientation**: Is the user able to find everything necessary in order to complete the task?
- **Duration**: How long does the user need to fulfill the task with each configurator?
- **Ranking**: Which of the configurators is considered to be the easiest to use? Which configurator is preferred in terms of joy in handling?

Defined Structure of the Configurators Used in the Experiment. To guarantee reliable testing objects, in cooperation with the initiators of the Configurator Database [22], four user interface structures of T-shirt configurators have been compiled. The identified structures represent used user interface structures of existing configurators in the fashion industry:

Technical Implementation of the Configurators. The configurators have been implemented by using the technology of Combeenation [9]. Probst et al. [8] describes Combeenation as an innovative solution for manufacturers of customizable products allowing them to sell their commodities online without initial costs. This software as a service enables clients to develop an all-in-one Web shop for their products. The configurators build by the clients can be modified and integrated into their own corporate Web site (Figs. 2, 3, 4, and 5).

Fig. 2 User Interface 1—fixed step-by-sep process navigation with labeled horizontal steps and toolboxes on the *right* side

Fig. 3 User Interface 2—flexible process navigation with toolboxes as accordion on the *left* side

Fig. 4 User Interface 3—flexible process navigation with opened toolboxes on the *right* side and at the *bottom*. The structure is adopted from Fig. 1

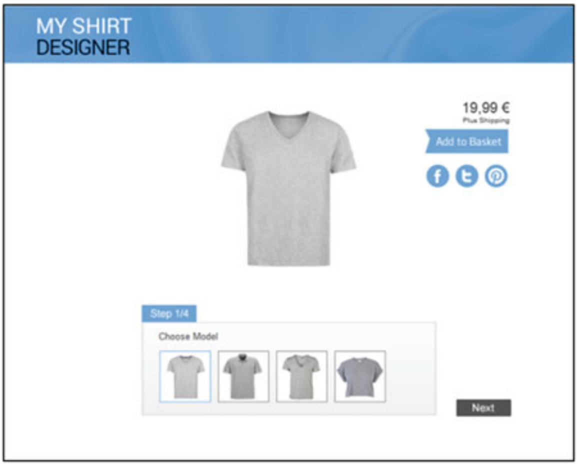

Fig. 5 User Interface 4—fixed step-by-step process navigation with unlabeled tabs and toolboxes at the *bottom*

3.3 Results and Key Findings

All 6 users have been able to create the defined T-shirts with all of the given configurators. The following findings can be clustered in "process navigation" (i.e., steps, buttons, accordion and general usability), "structure" (i.e., arrangement of the toolboxes, presentation of product and options and functionality) as well as in "overall ranking" and the investigation of the "duration" needed to finish the given task.

Process Navigation. Regarding process navigation, user interface 1 has been preferred the most. The subjects like the handling and the ease of use. In particular, the horizontal steps, which are labeled, are perceived as helpful during the configuration process. Switching back and forth in the process is easy, but it is annoying for all subjects to run through all steps again when one option (e.g., model) has to be changed subsequently. Also user interface 3 has been appreciated by the subjects as all configuration options are shown on one screen. There is no predefined way of configuring and thus leads to a very good usability in the subject's opinions. The user interface of configurator 3 is simple and very practical and offers the best functionality, compared to the other interfaces. More points of criticism have emerged at user interfaces 2 and 4. The subjects generally like the flexible process navigation of user interface 2. However, the toolbox as accordion, which opens and closes automatically, is not useable as it is annoying that the options disappear once another choicebox is opened. User interface 4 is not self-explaining. It is not clear which steps exist as they are not labeled. The separation in 4 steps is disturbing and should be replaced with labeled and clickable steps. The subjects dislike that the process navigation is only possible via next and back button. Subsequent changes are laboriously, because it is necessary to go back step by step.

Structure. In general, the subjects set great value upon a good overview and a big presentation of the product itself as well as the options. The toolboxes are preferred on the right side of the configurator, as in user interfaces 1 and 3. User interface 1 provides a very good overview as there is enough space for the toolboxes. The options and the product itself are shown big enough and the product is always in the center of the configurator. The necessary toolboxes are always opened and are well positioned. User interface 3 is also perceived very user-friendly as all toolboxes are opened. This interface provides a good overview of all options, and it is very clear and transparent. The roundly arrangement of the toolboxes (right and bottom) is not optimal as the interface looks filled up with tools and thus a little narrow.

The structure of user interface 2 is also judged quite good, because the product is always in the center of the configurator and all toolboxes are placed together on one side. Nevertheless, the interface looks narrow and the images of the different models are too small and not recognizable at a glance. User interface 4 totally lacks of overview. The models are very small and hardly recognizable.

Overall Ranking. All subjects have been asked to give an overall ranking of all four tested configurators concerning the satisfaction with process navigation and structure. The average ranking position is, with consideration of certain premises, as shown in Table 1. To sum it up, user interface 1 has been preferred most, because the subjects like the joyful guidance through the configuration process and the big product images.

Duration of Fulfilling the Given Task. During the user testing, the time needed to finish the given task has been tracked. The subjects have shown learning effects, as the duration of the configuration got generally shorter, no matter what configurator has been presented first as shown in Fig. 6. Figure 7 depicts that the duration difference between the user interfaces is marginal.

Table 1 Ranking of the tested user interfaces

Average ranking position	User interface	Premises
1	UI 1	When switching back and forth via the steps, the chosen options have to be memorized. There should be additional back- and next-buttons
2	UI 3	Another arrangement of the toolboxes is required, in order that the interface does not look filled up with tools. The images of the selectable options need to be bigger and the product image needs to give feedback immediately if an option is changed
3	UI 2	All toolboxes have to stay open. An accordion is only acceptable when there are lots of options. The images of the selectable options need to be bigger. Price information and cart button should be placed on the right side
4	UI 4	The steps have to be labeled and clickable. The navigation should also be possible via clickable steps or tabs, not only via next and back button. The back should be placed more present. The images of the selectable options need to be bigger. The price information and the cart button should be positioned on the right bottom side

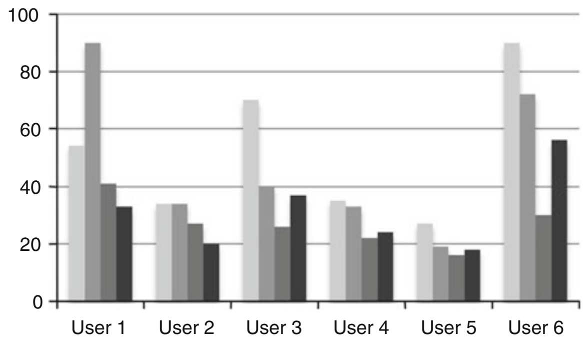

Fig. 6 Duration of completing the given task with the four user interfaces in seconds

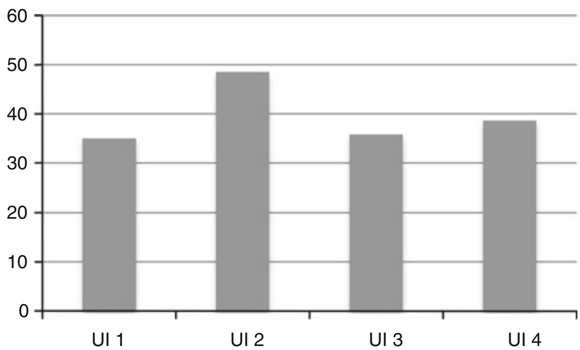

Fig. 7 Average duration of completing the given task per user interface in seconds

4 Conclusion and Outlook

The results show that the structure of user interfaces, considered in isolation, has an emotional impact on the satisfaction with the configuration process. It is indeed possible for the subjects to achieve the desired result with all user interfaces. However, clear preferences concerning the structure have emerged. Moreover, the testing detects that the structural standards Streichsbier et al. [7] gathered, which are represented in user interface 3, are not preferred by the subjects, but it is nevertheless voted on rank 2. These findings can of course not be generalized for all customizable products, as there is a high variety of product types, forms of customization, etc. However, there can be applicability for products of the fashion industry as well as products with a similar degree of complexity.

By a further gradual user testing, an optimization of the configurators could be certainly achieved. Combeenation [9] is seen as a suitable tool for this purpose, as the user interface can be adapted easily and quickly regardless of the underlying product data, which can certainly vary depending on the industry and product complexity. As the user testing is only a first insight into the importance of the structure of user interfaces for configurators, an adaptation of the configurators concerning the evaluated results and a further testing would be desirable. In a next step, it would be interesting to add the design components and make a user testing not only with the structure. Another exciting field of investigation would be the testing of the structure in terms of usability and ease of use on mobile devices such as iPads and smartphones.

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The Use of Modelling Methods for Product Configuration in Industrial Applications

Lars Hvam, Martin Bonev, Anders Haug and Niels Henrik Mortensen

Abstract Developing product configuration system (CS) requires extracting and representing domain expert knowledge in appropriate product models. As acknowledged by researchers, this is often one of the most challenging activities in configuration projects, where only little empirical insights have yet been reported. This article investigates the challenge on how industrial companies model their product CSs. The study is based on interviews of 18 industrial companies using CSs for configuring customer-tailored products. It investigates the relationship between using a structured modelling technique for modelling product families relative to less or no formal approaches. Furthermore, the study explores the specific characteristics of configuration set-ups with respect to size and complexity and their effect on product variant management and availability of product knowledge in organizations. The results empirically validate the need for a suggested systematic modelling approach for large and complex configuration projects and its positive effect on the overall performance of companies.

Keywords Mass customization · Product modelling · Product configuration · Object-oriented modelling

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1 Introduction

With product configuration systems (CSs), companies can obtain the growing product variety caused by today's global market competition in an efficient way [1, 2]. They represent one of the most successful applications of artificial intelligence principles [3–5]. A product CS is a software-based expert system that supports the users in the specification of customized products [6]. The system provides design choices for the user, while restricting the offered solution space to feasible combination of choices. Having a predefined knowledge base, CSs enable automating repetitive product specification tasks, for which human experts where previously needed. Their implementation has resulted in a number of operational benefits: such as reduced lead times, better quality of specifications, improved on-time delivery and less training for new employees [7–9]. In many cases, product CSs have been used to create quote prices, sales prices, bill of materials, and other product specifications. They incorporate knowledge-integrated or intelligent models of the product portfolio. Based on these models, new specifications for product instances and their life cycle properties can be derived. The development of CSs requires that domain expert knowledge is extracted and represented in corresponding product models to be incorporated in a CS. As acknowledged by researchers, this is often one of the most challenging activities in configuration projects [1, 4, 10]. However, only little empirical studies investigate the character of the modelling methods applied in industry and their usefulness with regard to nature of the configuration project. Instead, academia typically focusses on proposing various modelling methods based on conceptual examples or single case studies, e.g. [11–14]. To better understand this relation, this article evaluates the experiences from applying a structured approach for modelling product variants for product CS in relation to less formal methods. The implementation of a comparison framework for such a systematic approach is examined relative to less formal modelling techniques, e.g. structured bills of materials, or to no specific methods at all. The qualities of the suggested modelling procedure are yet not compared to other related modelling techniques.

2 Literature Review

2.1 From Real World to an IT-System

The development of a computer model can be expressed in several phases. Figure 1 shows the so-called phenomenon model and the information model as means for modelling real world objects for an IT-system. In the context of product CSs, such a transformation represents modelling product variants for a product CS. Based on the actual product family and its variants offered on the market, a phenomenon model is

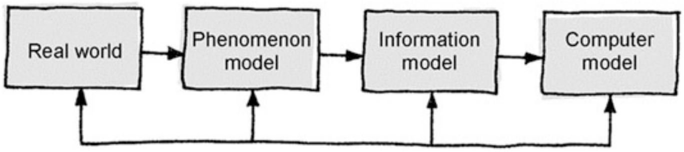


Fig. 1 From real world to an IT-system (adapted from [15])

developed and further formalized into an information model—an object-oriented model, which facilitates the transformation into an IT-system. Finally, the information model is implemented into a computer model, for which the same features and constraints are used, changed and updated across the phenomenon model, the information model and the computer model [15].

The challenge of modelling product knowledge has been discussed by several authors and alternative representation techniques have been suggested [1]. In the majority of cases, the proposed methods make use of the unified modelling language (UML) standard for the representation of the product knowledge and in particular of the information model [8]. Aldanondo et al. [11] for example introduce a combination of class diagrams, constraints expressed with natural language, as well as a number of inter- and intra-domain matrixes depicting the relationship between product components, operations or attributes. Chao and Chen [12] propose the use of a “general design” model, which expresses the relationship between components and assesses their ability for a physical assembly before production. Even though not discussed by the authors, the model makes partly use of the UML standard, e.g. to describe decomposition or cardinality. Also Magro and Torasso [16] investigate the possibility of providing a sufficient model for the representation of the product knowledge. The authors suggest a frames parts components (FPC) model, as a means of describing the relevant product knowledge. The mentioned technique can be seen as a modified UML model with a reduced syntax for the expression of, e.g. aggregation and generalization structures. Through its simplification, the authors argue for its visual support of sequential configuration algorithm examples. However, it remains unclear why the given and more comprehensive UML standard would not be at least just as suitable for the discussed configuration problems. Alternative methods have, e.g. proposed the use of feature or functional hierarchy trees [13, 17]. Based on such an initial meta-modelling of product functions, a more detailed configuration model is then acquired with class diagrams using the UML standard.

2.2 The Centre for Product Modelling Procedure

A more comprehensive approach has been taken by Hvam et al. [1]. The authors suggest a set of modelling techniques for modelling product families for product configuration [1]. The so-called Centre for Product Modelling (CPM) approach focuses on the phenomenon model and its transformation into an information model. The CPM procedure includes the use of a generic product variant model, the so-called product variant master (PVM) and class responsibility collaboration (CRC) cards for modelling product families. Here, a product model can be defined as a model that describes a product's structure, function and other product's life cycle properties, e.g. manufacturing, assembly, transportation and service [18, 19]. As it includes a definition of the rules for generating variants in the product assortment, it is used as a basis for a product CSs [1, 20]. However, experiences from a considerable number of industrial companies have shown that often these product CSs are constructed without the use of a strict modelling technique. As a result, many of the systems are unstructured and undocumented and therefore difficult or impossible to maintain or develop further [1].

In order to cope with these challenges, according to theory, the introduced method makes it possible to document the product CSs in a structured way. Furthermore, the modelling techniques enable to involve domain experts from, e.g. sales, product development and production in the modelling process. This improves the ability to make the right decisions on which products and features to include in the CS. Consequently, a stronger commitment behind the product knowledge implemented in the CS can be achieved.

The main principles of the PVM technique can be seen in Fig. 2. The left-hand side of the model contains the generic part of structure, also known as the aggregation structure from object-oriented modelling. The generalization which describes how a product part can appear in several variants, the so-called kind-of structure, is listed on the right-hand side of the model. In the PVM, a description is also given of the most important connections between modules/parts, i.e. rules for which modules/parts are permitted to be combined. This is done by drawing a line between the two modules/parts and writing the rules which apply for combining the modules/parts concerned. In a similar manner, the life cycle systems to be modelled are described in terms of masters that for example describe the production system or the assembly system. The individual modules/parts in the PVM are further described in CRC cards, which are used to detail the individual object classes [1, 19, 21]. They moreover contain information about product responsibility, version control or sketches and can be associated with both the PVM and the object-oriented analysis (OOA) model. The purpose of the CRC cards is to document detailed knowledge about attributes and methods for the individual object classes and to describe the classes' mutual relationships. The CRC cards serve as documentation for both domain experts and system developers, and thus, together with the PVM and the class diagram, become an important means of communicating and documenting knowledge within the project group. With their creation, a class diagram as an object-oriented model based on the UML standard can then be developed. Due to its systematic framework and the relative frequent use, the hereby described approach is further taken as a comparison model for a generally structured modelling procedure for CSs.

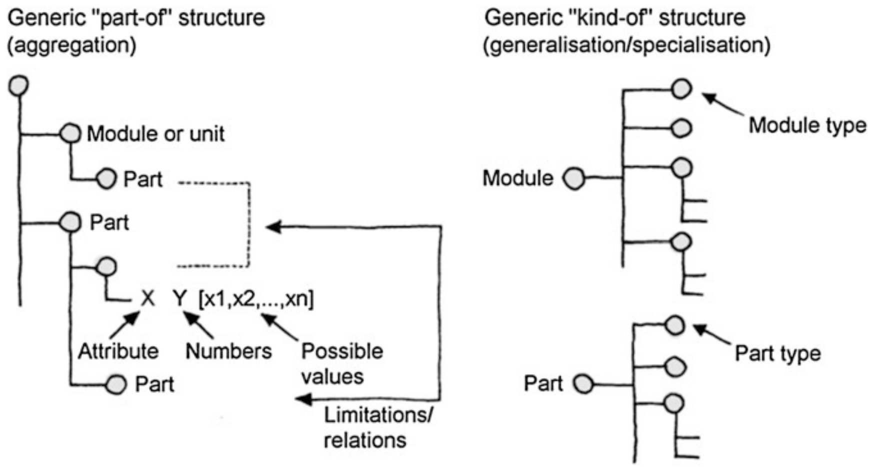
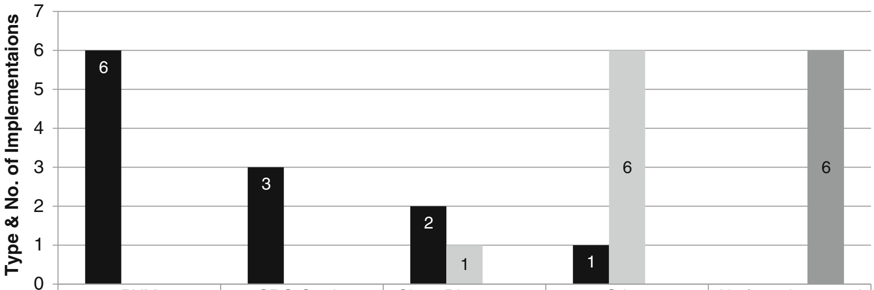


Fig. 2 Principles of the product variant master (taken from [1])

3 Research Method

To investigate the actual use of modelling techniques in product configuration projects, an investigation on the use of product CSs in industry companies was carried out. The study was conducted as semi-structured interviews of employees with knowledge of the configuration projects. The main reason for using interviews instead of a web-based or paper-based questionnaire survey is that the area in focus is characterized by a much unclear terminology. The chosen approach allowed for the interviewer to clarify the meaning of questions that are not understood and to rigorously investigate the nature of the configuration set-up. This option proved to be particularly helpful because of the different backgrounds of interviewees and the different industrial settings, definitions and practices of the target organizations. Furthermore, the research design made it possible to balance the breadth and the depth of the case studies by allowing for both qualitative explanations and quantitative indications.

A total of 26 companies were interviewed for the study, where a sample of 18 companies was selected based on: (1) the interviewed being able to explain the modelling techniques used and (2) the interviewed being able to state the effects from using product configuration. All 18 case companies offer business-to-business products, where in ten of them, several CS are in operation. The evaluation of the interviews enabled a general classification of the 18 companies with regards the modelling approach in three different categories, with six in each category. Figure 3 illustrates the modelling distribution for each of the categories. All companies belonging to category A were using the suggested PVM technique, three were using CRC cards and two companies also used class diagrams. Companies belonging to category B reported using structured bills of materials as their dominant way for



	PVM	CRC-Cards	Class-Diagramms	Other	No formal approach
■A	6	3	2	1	
■B			1	6	
■C					6

Fig. 3 Applied modelling techniques per category

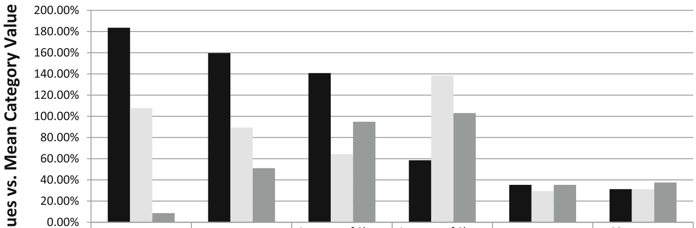
defining the variants in the product families. Besides, they apply Excel spread sheets, Word documents and the modelling environment provided in the product configuration software. The remaining C companies claimed not to use any specific modelling techniques outside the configuration tool, except of product tables in Excel spread sheets and specification reports in Word documents. The results of the configuration set-up in relation to the used modelling approach are discussed in the following section.

4 Results

4.1 Effects of the Configuration Set-Up on Company Size and Market

Figure 4 provides background information on the investigated companies and the size and purpose of their CSs. As indicated in Fig. 4, CSs are used across all three categories in support of the quotation and production process. More precisely, 17 out of 18 of the companies apply product CSs for quotations. Sixteen of these use the product CSs both for creating quotations and for the manufacturing specifications, while only one company uses product CSs solely for creating manufacturing specifications. In most cases, such product CSs were created by using the same standard configuration software shells. In the context of counting the number of product CSs, a single product CS is defined as being each running software application, which has an individual knowledge base.

Companies belonging to category A are typically globally operating firms, which are larger in average (84 % bigger than the mean value) and have a high share of customized products compared to configured ones. They are mainly offering industrial systems, plants and machineries, which require a strong engineering



	Average of No. of Empl	Average of No. of CSs	Average of Share From Customized Products	Average of Share From Configured Products	CS generates Quotation	CS generates Specifications for Production
A	183.55%	159.57%	140.81%	58.56%	35.29%	31.25%
B	107.78%	89.36%	64.33%	138.36%	29.41%	31.25%
C	8.67%	51.06%	94.86%	103.08%	35.29%	37.50%

	ID	Product Types
A	1	Plants, and machines
	11	Plants and electronic systems
	8	Boiler Systems
	7	Hydraulic Components
	10	Components and systems
	6	Ventilation systems
B	20	Building parts/ systems
	9	Building systems
	15	Agricultural Systems
	16	Control boards
	12	Heating Systems and components
	2	Mechanical systems
C	19	Agricultural Systems
	22	Building systems
	25	Building systems
	26	Tools and components
	27	Control systems and components
	29	Building systems

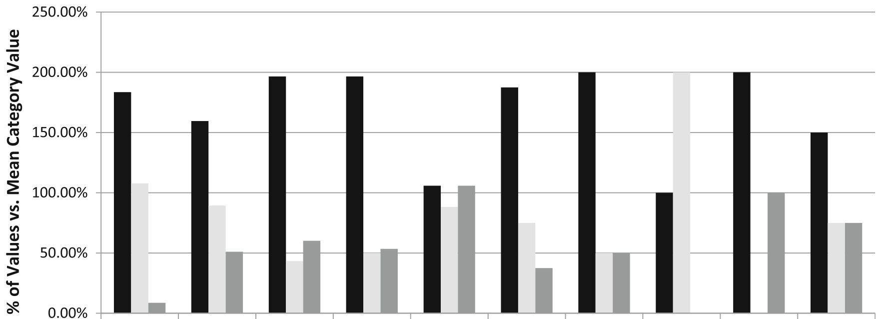
Fig. 4 Background information and configuration support

effort. To support the customization of their complex products, they have implemented several CSs (60 % more than the mean value). This helps them to configure ca. 30 % of their product range, while remaining part of their portfolio today involves additional engineering workload.

Compared to A firms, companies belonging to category B are in average smaller in size, yet globally operating. They are producing building, agricultural and mechanical systems and use a limited number of CSs for a large part of their product range. Next, C companies are considerably smaller in size. They are typically locally operating firms working within building and tooling sector, where ca. half of their products are supported by generally one CS.

4.2 Effects of the Configuration Set-Up and Complexity on the Modelling Approach

When investigating the detailed set-up of the individual CSs in the case companies, a major difference can be revealed. Companies in category A use several CSs for relatively complex products and with a strong integration to other IT systems (50 % more than the mean value), such as CAD or ERP. In order to handle the configuration tasks, each of their CSs comprise a large number of attributes and rules. Due to the increase challenges in modelling their product portfolio for configuration, all of the A companies were using the suggested CPM modelling techniques. But as the CSs grew bigger and the number of people involved in the configuration projects increased, they realized a need for being able to work in a more structured way and for being in more control of the models implemented in the product CSs. Here, three of the six companies using the CPM procedure have



	No. of Empl.	No. of CSs	No. of Attributes	No. of Rules	Int. ERP*	Int. CRM**	Int. CAD***	Int PLM****	Int. Calc*****	Total Integration
A	183.55%	159.57%	196.59%	196.58%	105.88%	187.50%	200.00%	100.00%	200.00%	150.00%
B	107.78%	89.36%	43.29%	50.00%	88.24%	75.00%	50.00%	200.00%	0.00%	75.00%
C	8.67%	51.06%	60.12%	53.42%	105.88%	37.50%	50.00%	0.00%	100.00%	75.00%

***Enterprice Resource Planing **Customer Relationship Management ***Computer Aided Design**
******Product Lifecycle Management *****Adcanced Calculations (e.g. MathCAD)**

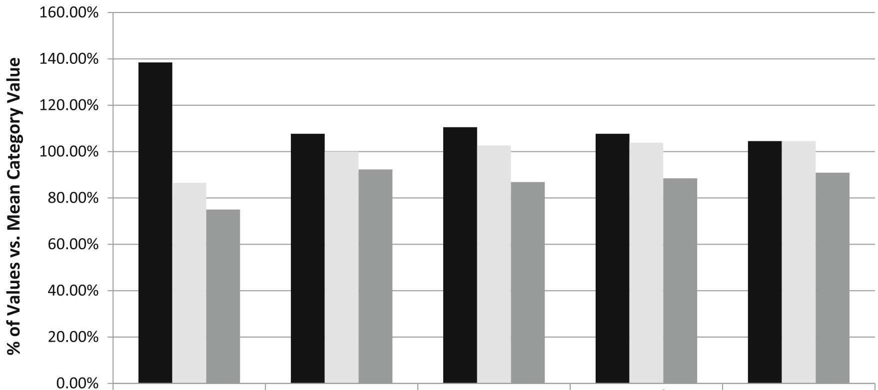
Fig. 5 Effects of product configuration complexity on system integrations

reported that they started to model their product CSs without any specific modelling technique.

As Fig. 5 reveals, companies of category B and C have implemented significantly smaller CSs. Their systems are usually integrated to enterprise resource planning (ERP) or product lifecycle management (PLM) systems, with little emphasis on external integrations to computer-aided design (CAD) or to advanced calculation systems. This indicates that with a minor configuration project for relatively simple products and not involving too many employees, the modelling can be managed by using less formal modelling tools. As the configuration task increase in both, size and complexity, the more important becomes a systematic modelling approach.

4.3 *Effects of the Configuration Set-Up on Companies' Performance*

Finally, the impact on the companies' ability to document and share their product knowledge, their ability to reduce the number of product variants in the company and the degree of employee satisfaction among the employees involved in the product configuration projects was investigated. The respondents have rated the impact on a five-point scale from 1 (strongly disagree) to 5 (strongly agree) and "empty space" for no answer to the question. Here, reducing product variants means the ability to eliminate unnecessary product variants from the product assortment in the company. The ability to keep down the number of product variants (item numbers) in the product assortment is claimed to be an important enabler for reducing complexity and thus keeping down costs in the company



	Average of Red. Item No.	Average of Inc. Use of Std. Mod.	Average of Impr. Knowl. Doc.	Average of Impr. Prod Know. Availability	Average of Inc. Empl. Satisfaction
A	138.46%	107.69%	110.53%	107.69%	104.55%
B	86.54%	100.00%	102.63%	103.85%	104.55%
C	75.00%	92.31%	86.84%	88.46%	90.91%

Fig. 6 Effects on work environment, knowledge management, product design and quality

[22, 23]. As listed in Fig. 6, A category companies claim to have a better ability to reduce the number of product variants than the others. This may be related to an increased ability to document and get access to product knowledge with the CRM procedure. Companies not using the CPM procedure report to have less documentation of, and access to, their product knowledge. However, the differences between the three groups on documentation and accessibility of product knowledge are not very significant. This could be related to the fact that the companies using less formal modelling techniques are having relatively minor CSs, which handle simpler configuration tasks and where the related complexity can still be managed.

Furthermore, employees working on product configuration projects with the described formal modelling procedure report to be slightly more satisfied with their working situation than those working with no formal modelling techniques. This may be related to the increased ability to document and get access to product knowledge, which makes it easier for the employees to control the product knowledge implemented in the CSs and to communicate the product knowledge with colleagues from other departments, such as product development, sales and production.

5 Conclusion

The conducted study on the use of product CSs in industrial companies provided new insight into how CSs are modelled and documented in relation to the nature of the configuration set-up. The results reveal that out of 18, six companies used the suggested systematic modelling approach, namely the CPM procedure, for relatively complex products and sophisticated CSs. The remaining 12 companies used less formal or no formal modelling techniques for less challenging and less advanced configuration projects. Furthermore, three of the six respondents using the CPM modelling techniques have claimed that they started to use the more formal modelling techniques as the number of CSs and thus the configuration projects grew bigger and involved more and more people. They then claim to be more in control of their product knowledge and their product variants than the companies using less formal modelling techniques. This may be partly due to an increased ability to involve domain experts in the modelling process, which secures that the right decisions are being made as to which product variants to include in the CSs. This indicates that in order to major companies to be successful in the use of product CSs in a setup with several CSs with a high complexity and numerous employees (often geographically diversified) involved, a formal modelling technique like the CPM approach is needed. Furthermore, a more formal modelling technique makes it possible to keep track of the product variants, features and rules implemented in the CS. A better communication with the domain experts reflected in the report an increased ability to control the product knowledge as well as an increased level of satisfaction from the employees working in the configuration projects. The study revealed an important correlation between the use of a formal modelling technique (the CPM approach), the size and complexity of the CSs as well as the ability to control the product knowledge and products variants. However, having obtained these results, further questions are being raised as to, e.g. which specific features of the modelling techniques leads to an increased control of the product knowledge, or what is the correlation between the use of a formal modelling technique and the capability to successfully implement a product CS. Moreover, to better generalize the results, it would be beneficial to expand the number of industrial cases.

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Understanding Complex Construction Systems Through Modularity

Tor Clarke Jensen, Baris Bekdik and Christian Thuesen

Abstract This paper develops a framework for understanding complexity in construction projects by combining theories of complexity management and modularization. The framework incorporates three dimensions of product, process, and organizational modularity with the case of gypsum wall elements. The analysis finds that the main driver of complexity is the fragmentation of the design and production, which causes the production modules to construct and install new product types and variants for each project as the designers are swapped for every project. The many interfaces are characteristics of an integral system, rather than a modular, although the industry forces modular organizational structures. This creates a high complexity degree caused by the non-alignment of building parts and organizations and the frequent swapping of modules.

Keywords Modularity · Complexity · AEC · Construction · Project-based production (PBP)

1 Introduction

The architecture, engineering, and construction (AEC) industry differentiates from other production-based industries by its unique properties. The project-based production (PBP) nature of the construction industry combined together with size of the projects causes high complexity. Researchers such as [1] and [2] define the projects as hyper-complex, but do not explain where this complexity arises and evolves. Although sub-products such as gypsum walls are produced according to mass production principles, the final construction product is very much tailored

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according to the highly varied PBP requirements. Therefore, the uniqueness of each construction project involves great challenges in terms of mass customization. The ambition of the paper is to explore the construction industry from a system perspective, as a complex production system. The main idea is to understand the project-based environment of construction through concepts such as modularity and complexity management, which have been developed as a system analysis for operation-based businesses, and thereby potentially enables the application of mass customization principles in construction.

2 Methodology

The research is conducted through an abductive case study combining theories of complexity and modularization with empirical material from a standard construction practices: gypsum walls. The empirical data were collected through semi-structured interviews [3] with the various parties such as architect, project director, and carpenters, which all participate in the design and production gypsum walls. A detailed analysis of a gypsum wall (sub-product) being assembled (process) by a carpenter (organizational unit) will be the core point of this paper.

3 Literature Study

The two theories, complexity and modularity, that the research is based on encompass similar and compatible concepts. They both have a focus on product, process, and organizational aspects (PPO). In this paper, the two theories are brought together in the attempt to understand the highly complex production systems within construction.

3.1 Complexity

Complexity and complex system are not necessarily about large numbers. Appelo [4] describes how small systems such as a single water molecule are complex, because its actions are not easily predictable. This is in opposition to causality, which says that a certain cause will have a specific effect, which characterizes linearity, predictability, and determinism. Complex systems are thus nonlinear and very difficult to predict.

Wilson and Perumal [5] argue that understanding and analyzing complexity is crucial for developing organizational efficiency. In their perspective, products, processes, and organizations are related and all have their own role of complexity; however, managing each subject alone will not provide much improvement compared to a combined approach.

The Product Complexity arises from a variety available to the end customer. It is a tough balance between having enough variety and too much variety; too little will send market shares to competitors, while too much will make products cannibalize on existing products' market share [5]. The actual introduction of new packages, products, or other product-related innovations also increases process complexity, as this results in increased variety through the whole value chain [6]. Wilson and Perumal [5] subdivide product complexity into external and internal, where the external is the actual product range. The internal product complexity is derived from the elements, which are used to create the product such as parts, specifications, and instructions.

The Process Complexity arises through the amount and dependencies of processes within a production chain. The more direct the production chain is, the less the complexity costs are associated with the product, while rework and work-around are consequences of too much complexity. Reducing process complexity is very similar to the lean concept of process waste and non-value-adding processes. Wilson and Perumal [5] say that process complexity and non-value-adding costs can be treated as equivalent at a practical level, but technically they are different.

The Organizational Complexity of a company is related to the amount of organizational units, systems, and assets, which the company involves in performing its processes. The complexity of the organization and the processes are strongly linked, and the organizational complexity usually arises to cope with the increased complexity of the processes [5]. Ashkenas [6] describes how incremental change can increase the organizational complexity, as small tweaks keep adding complexity and this often goes unrecognized.

Intersection between different types of complexities. Wilson and Perumal [5] argue strongly that the main reason for complexity to arise is the relations between the three dimensions of product, process, and organization. These are related through the complexity cube, which is a three-dimensional diagram with an axis for each dimension as shown in Fig. 1. The further from the center, the more the complexity, and this means that the complexity is multiplied rather than added for each dimension. As Wilson and Perumal [5] treat complexity costs and non-value-adding costs equally, this also means that the degree of non-value adding will increase steadily with the company generating less revenue.

Product/process face—Where complexity arises. The product variety strains the performance of processes producing the product, and this influences the profitability of the product. As the processes are required to deliver the product, these constitute a substantial part of the product cost. The processes are, however, not isolated to a single product, but are connected to a series of products, which accumulates the overall cost of delivering the products.

Process/organizational face—Where complexity hides. As the process is how a work is delivered, the process/organization face is about how the organization deploys its resources to execute these processes. This face is the least tangible, as processes are dispersed between organizational functions, which may be divided into silos, and the holistic view of the processes is thus lost. The amount of resources required for a given process is thus not visible without any in-depth analysis.

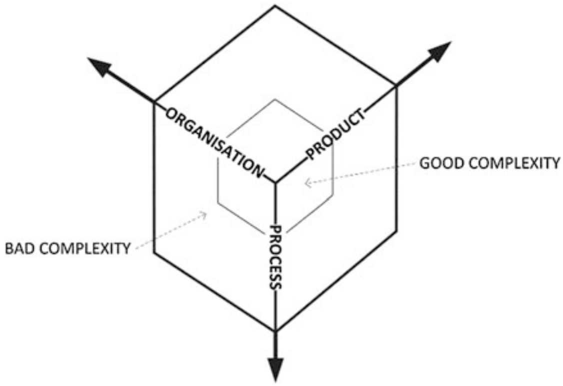

Fig. 1 The complexity cube. Modified by author from original in Wilson and Perumal [5]

Organizational/product face—Where complexity takes root. This is where organizational resources are allocated to the products of an organization. These resources include physical assets, organizational structures, and supply chain partners. This face has the largest need of investment and thus holds most assets such as facilities, technology, and IT systems, but also increased cost with a fragmented supply chain and rivalry between functional units. The organizational/ product face will always seek to optimize itself according to the given conditions, so the organization and products become dependent on each other. The roots occur through a series of iterations, where the product portfolio cannot be reduced because the assets will be obsolete and the assets cannot be reduced because these support the product portfolio. The complexity thus becomes trapped and cannot be controlled unless both the product and organization are considered simultaneously.

3.2 Modularity

According to Campagnolo and Camuffo [7], there exists no single accepted definition of modularity, but a series of common traits which are generally applied. The main trait as Simon [8] describes is that systems consist of hierarchies of modules and interdependence within a module is stronger than the interdependence between modules. The modules interact with other modules through standardized interfaces, which also allow a decoupling of modules. Campagnolo and Camuffo [7] argue that a modular system is in opposition to an integral one, which provides an axis of analysis, measuring systems according to modular versus integral structure.

Given the broad acceptances of the concept, Campagnolo and Camuffo [7] argue that every system is modular to some extent. This gives rise to different ways of understanding and describing modularity.

In Campagnolo and Camuffo's [7] review of the concept of modularity, they identify three streams of literature clustered around three different units of analysis: (a) product design modularity, (b) production system modularity, and

(c) organizational design modularity (p. 260). Based on Thuesen [9] reinterpretation of the modularity concept, these categories are in the following referred to as product, process, and organizational modularity.

Baldwin and Clark [10] describe how modularity is a strategy to manage complex products and processes. Managing modularity deals with hidden and visible information, where the hidden information covers the interdependency within the modules. The visible information is concerned with the overall architecture, interfaces, and standards, which all cover external information for each individual module. In this relation, architecture is the dominant aspect of modular systems, as this describes the modularity principles, functions, and interaction. In order to manage modularity, the architecture has to be apparent and this has to be in control of the architect [10].

3.3 Complexity and Modularity in Construction

A construction project is unique, while a mass production is repeated. Bertelsen [2] accepts that projects can be defined as production, but says that in order to understand the construction projects, a complexity approach also has to be applied. He defines construction projects as complex systems which cannot obtain optimality: neither in design nor in production. Projects are thus unpredictable and nonlinear and cannot be followed through specific linear phases and with independent organizations.

The complexity of construction projects means that traditional learning through experience does not necessarily increase efficiency over time. Traditional construction always incorporates a number of crafts into the construction organization. Depending on the project and contract type, the client will hire the contractor/contractors to perform the actual production as well as consultants to perform the program and design. The contracting organization may be organized in different configurations (or architectures), but are generally divided into subcontractors consisting of individual companies or organizational units according to crafts or professions. Relations between a client and contractors or main contractor and subcontractors are usually established through tenders, and the ensuing relationship is upheld through contracts.

The organization is thus modular to the extent that crafts can be interchanged and the contracts act as standardized interfaces and their also exists a number of platforms. Standards for organizing projects, such as AB92, exist for the Danish construction projects, so this matches the definition of modularity of Baldwin and Clark [10], but in particular, the architecture is difficult to translate into a project environment. The modularity combined with complexity together with the advantages and challenges in the application of construction sub-product will be analyzed in the following section.

4 Analysis of Gypsum Walls

The detailed analyses of the gypsum wall production as a construction sub-product are studied in this section. As explained earlier are the empirical data collected through a series of interviews. Figure 2 illustrates a general overview of the gypsum wall production including the process and the involved organizations.

Gypsum walls have become the standard choice for partition walls, as it is the easiest method of establishing partitions between rooms. They also have a low cost compared to their high acoustic and fire protection rating. In addition, they have a good constructability as they are very flexible and easy to get into the building. An example of a gypsum wall is shown in Fig. 3.

4.1 Case Analysis

The gypsum wall application case will in the following be analyzed with a product, process, and organizational focus.

The product focus. The products or sub-products in question are the gypsum walls, which are divided into a series of variants/types. The gypsum walls consist of steel profiles with screw-mounted gypsum boards with insulation material in between. In addition, the walls are plastered and painted and some include technical installations, mainly electrical installations. The gypsum wall types are differentiated by the components: three types of steel profiles, two types of gypsum boards, and three types of insulation (more component types may be procured). The structure also differentiates between single or parallel steel profiles, number of boards, boards on one or two sides, and single or double insulation. The actual sub-product module is defined as all internal or directly mounted components on the gypsum wall without other interfaces.

In addition to the actual module, a series of interfaces connect the gypsum wall to other sub-products. The most direct interface is with the (concrete) slab elements, as in Fig. 3, which supports the wall at bottom and top. The penetrations of technical installations are also considered interfaces as well as ceilings, floors, glass walls, (concrete) wall elements, and façades. This leads to two kinds of interfaces: penetrating interfaces and mount interfaces, which could be subdivided into line and point (for TVs, etc.). Internal electrical installations should also have an interface to the electrical supply system. The product interfaces are not specified on components or material, but are established on-site according to the erected sub-products. The main means of performing the actual interfaces are through screws, glue, or sealants. Each single wall may have different interfaces, as these are determined by the different designers.

Although the initial product coming directly from factory is a mass production product fitting pick-to-order (PTO) scenario, the variety between the gypsum walls and their established interfaces could mean that all walls are individual and therefore follow an assemble-to-order (ATO) process.

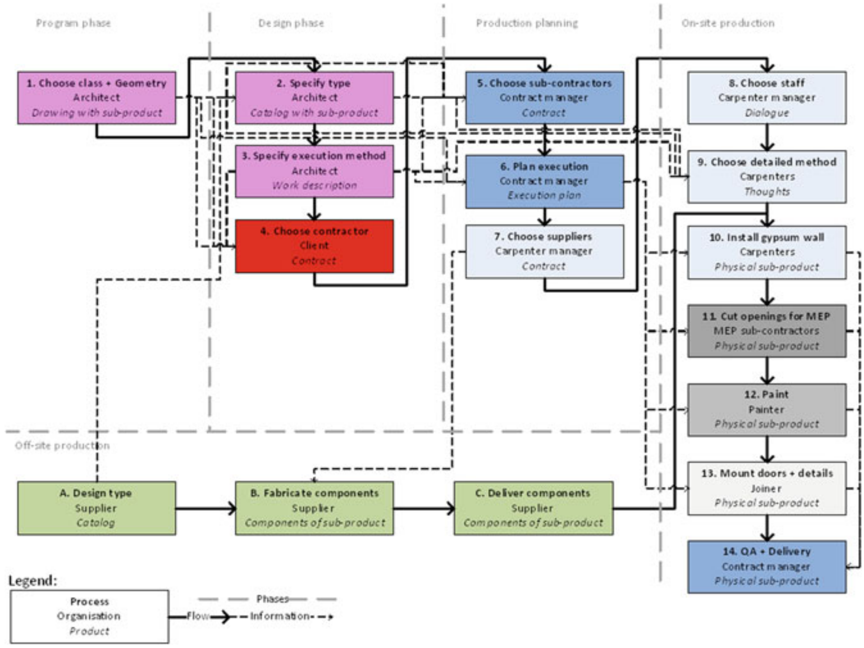

Fig. 2 The value chain of gypsum walls including products, process, and organizational entities

Fig. 3 Gypsum wall production from different perspectives

The process focus. The processes are generally derived from the current product structure and by the crafts traditional work method. The gypsum walls have a set of production processes described in the supplier manual and design information. These processes include erecting steel structure, installing insulation, mounting gypsum boards, installing electrical installations, plastering, painting, mounting doors, and detailing/finishing. These processes are delegated to the crafts according to their traditional domain. The actual production process is thus dominated by the product, which specifies the processes, while the organizations are chosen according to specified processes. Specifying wall type mainly involves creating information on the specific requirements for the individual wall and otherwise following the supplier's manual for attaining these properties. This would suggest a simple process of specification to construction, but as architect explains how information generated may change through the design phase, this will have consequences for the production processes. A process module with similar input and output could be swapped and shared. Knauf Danogips [11] describes mounting gypsum boards: These can both be fixed with screws or glued in place. This does not change the previous process (erection of steel profiles) or subsequent process (plastering), but the three processes cannot be swapped.

The processes themselves are not specifically defined. Both carpenters say that the individual task can be performed in many different ways. The process of aligning the steel profiles is not described. This would imply that the process interfaces are standardized across crafts, but not within them.

The architecture of the project and the amount of interfaces may result in the final gypsum wall product to contain the characteristics varying from ATO process to even engineer-to-order (ETO) process of mass customization scenarios presented by Hvam [12].

The organizational focus. By following the value chain, the main organizations who are involved in the construction of the gypsum walls are architect, carpenter contractor, electrical contractor, painter contractor, and joiner contractor. Other organizations are more indirectly involved, and these include gypsum supplier, consulting engineer, design–build contractor, technical contractors, and possibly other contractors. The departments or project teams of the companies who are involved in the project are defined as organizational modules. The organizations involved in the project also work on other sub-products. The architect is involved in all the non-technical sub-products, while the carpenter is also responsible for construction of ceilings, floors, window sills, and skirting.

Although some of the organizational modules have continuous relationships, these are not actually predefined partnerships. Project director states that although the carpenter contractors are part of the case company, they are only considered if they can perform at a competitive price, and otherwise, another carpenter contractor would have been chosen instead. The architect and consulting engineer are neither permanent partners, so these will also be swappable.

The organizational modularity is evident according to the swap-within and share-across aspects. The question is whether the standard interfaces occur. As these are defined as interaction between organizational modules, the interaction must be standardized. An example of this could be the project clarification, which is used by the carpenter to clarify inconsistencies or alternatives in the architect's specification.

A topic, which has not been described by the literature, is the individual's role within the organizational modules. Both complexity management and modularity are based on industrial production or service companies, which mainly work through operations and permanent employees. The project organization of construction systems creates an environment, where the craftsmen do not follow specific organizational units and the different types of functional organizational modules can consist of different companies from project to project.

The PPO-module. The modularity of the product and organization is clearly not aligned, because the sub-products are designed and produced by several organizational units and the organizational units design or produce a series of sub-products. The process modularity dictates which and when the organizational modules are applied. The PPO-modules, which include all three dimensions, cannot follow the described modularity.

The different organizational units only deliver part of the product. The architect delivers a design represented by drawings; the carpenter contractor delivers a steel structure clad with gypsum, the painter delivers plaster and paint to the surfaces, and the joiner delivers doors. The electrician may also install some components within the wall. Meanwhile, the organizations and individuals are split on a series of other sub-products with other associated processes. This provides a structure where the products are divided into materials which dictate processes and organizations.

The PPO-module of carpenter contractor/gypsum wall will include the processes of steel profile erection, insulation installation, and gypsum board mounting. The gypsum wall will, however, also all have PPO-modules of architect, electrical contractor, painting contractor, and joiner contractor. All PPO-modules of the gypsum walls are presented in Fig. 4. The modules will thus be a clustering of processes, and these will also determine the sequence of PPO-modules. The carpenter contractor and individual carpenters will also be part of a series of other modules.

Assessing interfaces. The PPO-module of gypsum wall/carpenter contractor has been analyzed, and the definition of interfaces along the three dimensions has been established. This creates a total of 32 interfaces with 15 other PPO-modules as shown in Fig. 4. The figure is based on conservative estimations of the empirical data and may include more as many of the other sub-products and organizations have not been investigated in any detail.

Product interfaces. Figure 4 shows the 13 product interfaces for the gypsum wall/carpenter contractor, which corresponds to the following:

- Internal: architect drawings, gypsum components, electrical, plaster/paint, doors, details/finish
- External: concrete slabs, concrete walls, façades, glass walls, technical installations (HVAC, electric, sprinkler, etc.), ceilings, floors

The internal products' interfaces all appear in the supplier's manual and are regular. The external interfaces are more irregular, but interfaces with the concrete structure and technical installations are described in the manual. Architect says that mainly interfaces toward the façades and glass walls are specifically designed for the project, which suggests that these are irregular.

Process interfaces. Figure 4 shows the seven process interfaces with for the gypsum wall/carpenter contractor, which corresponds to the following:

- Previous: specifying wall class and specifying wall type, manufacturing components, mounting slab elements
- Subsequent: installing electrical installations, plastering/painting, mounting doors, and detailing/finishing

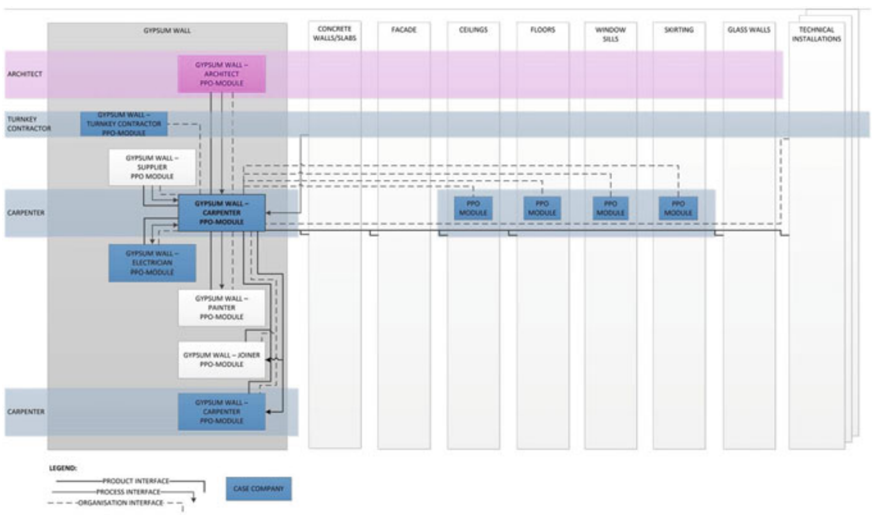

Fig. 4 Interfaces of the gypsum wall/carpenter contractor PPO-module

The process interfaces follow a sequence caused by the process constraints. These mainly follow the supplier's manual, but processes where the supplier is not involved are not described. Architect says that the specification process consists of dialogue with different organizational units such as the client, consulting engineers, and carpenter contractor, which must lead to a series of iterations and thus limits the consistency of the process. The product interfaces which are not regular such as the façade and glass walls will thus not be regular in the process of establishing these interfaces.

Organizational interfaces. Figure 4 shows the 12 organizational interfaces for the gypsum wall/carpenter contractor, which corresponds to the following:

- Internal: design–build contractor, electrical contractor, carpenter (finishes), carpenter (ceiling), carpenter (floor), carpenter (window sills), carpenter (skirting)
- External: Architect, Technical Contractors (HVAC, Electric, Sprinkler etc.), Painting Contractor, Supplier, Joiner

The organizational interfaces are mainly performed through the management such as project director. The main exception to this is the electricians, and this creates a less regular interface from an organizational view, as each individual carpenter thus has interaction with the electrician module instead of this going through the management.

Assessing variety. The variety within the case project should be determined across the three dimensions. The possible variety within the PPO-module will be 14 different wall types, 80 different carpenters, and up to 80 different methods. The carpenters and methods are, however, connected to each other, as each carpenter has their own method, but only if one carpenter works on each wall. The wall types will thus contribute to the highest variety for each individual carpenter. The walls are, however, determined not only by type, but also by geometrical variety. The variety of geometry will increase the variety way above the 14 types. The placement of doors and other components of the wall is neither part of the type, so will increase variety. So when all instances of walls are considered, these will potentially lead to all gypsum walls as unique.

The PPO-module across projects. Although most interfaces are regular to a certain degree and the variety is mainly limited to the different types and geometries, this is only for the case project. Through the interviews, a strong focus has been on the variety of products and processes as well as relationships of organizational units across project. The gypsum wall/carpenter contractor PPO-module is set in the center when assessing it across projects, so other PPO-modules will be swapped rather than gypsum wall/carpenter contractor.

The wall types must be similar, as they are based on the suppliers' manual, and although different suppliers advise the architects, the case company only has a single supplier. The architect, however, dominates all decisions regarding geometry and extra components, which increases variety further.

The organizational interfaces are not as similar across projects as the product and process interfaces. Only few of the organizational units have worked together before, and these are not permanent partnerships. Although it is an advantage that the individuals of the organizational units know and trust each other, the main determinant of an organizational unit's involvement is the price. The main representatives of the organizational units are the managements, while the craftsmen are not permanent employees within the companies.

4.2 Assessing Structural and Operational Complexity

The variety of the gypsum walls is very high as almost all walls will be unique through their geometry or embedded and mounted components. This creates a high structural complexity for the sub-product. Although the detailed methods are very varied, these do not increase structural complexity as methods are embedded within each carpenter, so as long as carpenters are responsible for each wall, this will not result in a large increase. Across projects, the amount of structural complexity will increase even more, because of the unique geometry. The carpenter contractor's permanent agreement with the gypsum supplier reduces not only the sub-product variety, but also the processes. Contrary, the individual carpenters may change company from project to project. The structural complexity is thus high within the case project driven by the sub-product, while both the organizational and sub-product varieties will increase structural complexity across projects.

The interfaces of the gypsum wall/carpenter contractor are very numerous, which leads to a more integral than modular system. The interaction between the carpenter and electrical contractor is especially strong, and the regularity is mainly controlled by the individuals knowing each other. Across projects, this interface will be a strong driver of uncertainty, as the two interacting PPO-modules may be exchanged from project to project. This will create different relations between the PPO-modules and thus increases uncertainty. The rest of the interfaces are managed through the contractors' managements and so will not increase the uncertainty when assessing the case project, but across projects, this will accumulate and increase operational complexity further. This results in a high operational complexity between the gypsum walls' carpenter and electrical contractors, while the other interfaces only provide a medium operational complexity.

5 Discussion

As the current construction system is neither optimal from a modular nor an integral approach strategies for managing, both operational and structural complexities are proposed. This is summed up and related to other ideas for developing a new construction system. The product modularity and organizational modularity are currently misaligned, as the product modularity and organizational modularity follow different hierarchies. This creates many individual PPO-modules and many strong interfaces and thus increases the operational complexity.

If a more integral organization was to be applied, these strong interfaces could provide more regular interfaces, especially organizational interfaces. This creates Development Initiative 1 (DI1) to manage operational complexity:

- DI1: Create regular partnerships with all organizational modules and thus use similar products and processes for all projects.

This initiative maintains all current interfaces within the individual projects, but stabilizes these across projects. By letting the same individuals work together, this creates regular interfaces, and especially if the design modules use similar designs, this will influence the product and processes to apply similar interfaces. DI1 would automatically create a more integral organization, with more focus on partnerships and permanent relations than flexibility, which will have to be incorporated into the system according to the actual need.

Another approach could be to align the product and organizational hierarchies. Ericsson and Erixon [13] describe this system as "small factories within the factory" and thus following an integrated value chain for each sub-product. This would require multiple crafts within the same PPO-module and possibly also design capabilities. The PPO-structured modularity will thus comprise of less PPO-modules and less interfaces by integrating the supply chains for each sub-product into single modules. This creates Development Initiative 2 (DI2) for managing operational complexity:

- DI2: Aligning the organizational modularity with the product modularity and creating PPO-modules by integrating all processes and organization. An illustration of DI2 is shown in Fig. 5.

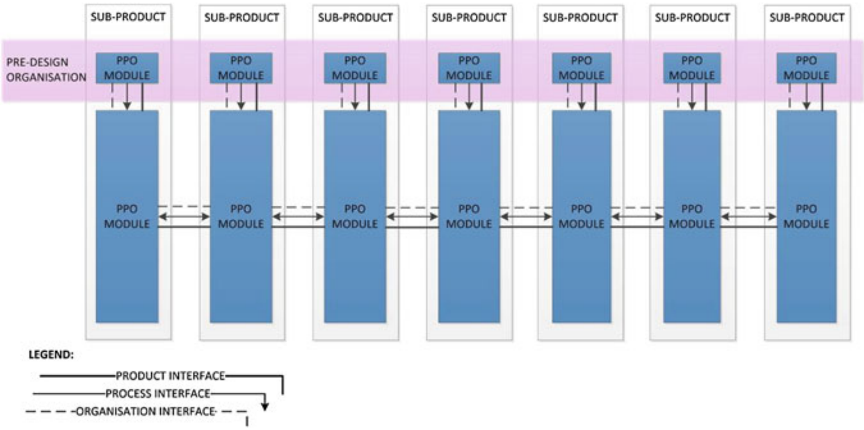

Fig. 5 An example of how the PPO-structured modularity could be implemented through Development Initiative 2. Development initiative 1 would resemble the interfaces and structure found in Fig. 4 for all sub-products

This would require sub-product contractors rather than craft contractors. The integrated PPO-modules would increase dependencies within and decrease dependencies without compared to the existing structure. DI2 will also ease procurement and outsourcing of sub-products. This will help create system architecture, so also interfaces and standards could develop. The system architecture will increase flexibility as the PPO-modules integrating a sub-products value chain can be exchanged at will.

The construction system is currently a mix of strong interfaces and flexible modules in all three dimensions. The two solutions thus go in two different directions: more integral or more modular, where either the interdependence or the exchange of modules shall be reduced. The paper has also found connections between operational complexity and modularity. As systems become more integral, the amount and strength of interfaces increases. This causes the operational complexity to increase, and when modules are swapped and shared, this operational complexity increases drastically.

Modularity is applied on many levels, and this paper has explored modularity on a holistic level, especially product modularity of industrial production requires very specific interfaces. The interfaces of construction sub-products are dominated by less-defined point, line, and surface interfaces, where sub-products can be mounted onto the bearing structure at will. Ulrich and Tung's [14] cut-to-fit modularity thus becomes dominant, while still retaining the swap-within and share-across modularity.

Based on the findings and experiences gathered through the case, it is concluded that the principles of mass customization of a sub-part can be successful when implemented stepwise. The case shows that substantial benefits can be gained through implementing modularized construction. It is especially interesting to note that these benefits are achieved through the development of a module with focus on the internal interfaces [15].

The generally craft-based organization thus seems to be a remnant of the past. Current implementations of ICT in the industry, such as BIM, do not fit well into the current construction system [16], but could be heading development toward a new system, which organizationally would be more operation based. As shown in the analysis is the current system very fragmented, and the development is difficult to implement rationally in such a system [17]. As is often said when discussing industry competition: "Supply chains, not businesses, are the competitors of tomorrow."

6 Conclusion

The complexity in construction projects arises because the system is integral, but acts modular. The integral property arises because the misalignment between the product modularity and organizational modularity and combined with the fragmented organization, variety, and interfaces cannot be managed, especially as the design and production are performed by different organizations.

The paper has attempted to show that the PPO-structured modularity can link the dimensions of product, process, and organization into a common system. The PPO-modules are developed by combining product, process, and organizational modularity into a common structure where the interfaces are also defined across all three dimensions. The PPO-structured modularity is based on the complexity cube and thus uniting modularity with complexity management. This has also added to both concepts, mainly through linking operational complexity with the modular-integral continuum. Applying PPO-structured modularity to a project environment was applicable, and the case project showed how gypsum walls have a dispersed supply chain, with 32 interfaces from a contractor perspective.

PPO-modules of gypsum walls provide variation possibilities and thus serve perfectly to individual customer needs. The different combinations of PPO-modules enable various numbers of solutions, thanks to the flexibility and creativity they possess.

This paper has also developed paths for the industry to pursue in order to manage complexity. This involves developing the construction system as either more integral or more modular, where the integral path is to standardize PPO-modules of the current system through permanent partnerships, while the modular path aligns the organizations according to the sub-products.

This will generate the level of process stability that mass customization highly depends on. Thus, modular production of the studied construction product gypsum wall contains great promises for applying mass customization principles within PBP.

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