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Stephan Hankammer · Kjeld Nielsen
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Ning Wang *Editors*

Customization 4.0

Proceedings of the 9th World Mass Customization & Personalization Conference (MCPC 2017), Aachen, Germany, November 20th-21st, 2017

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Preface

From Mass Customization to Customization 4.0

More than two decades after the inaugural publications and first applications, Mass Customization and Personalization (MCP) are among the hottest topics of digital business models today. MCP strategies aim to profit from the fact that people and businesses are not all the same but different in their needs. Their objective is to turn customer heterogeneities into profit opportunities by realizing "long tail" business models with near mass production efficiency.

The MCPC conference series has been following and facilitating this development since 2001. Its ninth edition, the MCPC 2017, took place at the RWTH Aachen University, one of Europe's leading centers for technology and innovation, in November 2017. The current trends of Industrie 4.0, digital manufacturing, and the rise of smart product ecosystems allowed for a fresh perspective on MCP: Customization 4.0. A diverse group of delegates from industry and academia explored how these technological enablers can create a new breed of mass customization business models.

The conference has also placed a new set of values in the center of the debate. A world with finite resources, global population growth, and exacerbating climate change mandates smart thinking and the engagement of the most effective capabilities and resources. At the MCPC 2017, we discussed how Customization 4.0 fosters sustainable development and how shared value for companies, customers, consumers, and the society as a whole could be created.

While we devoted the conference to sharing and discussing the latest research in the field, the MCPC 2017 also had a strong focus on commercial applications and entrepreneurial ventures. This is what makes the MCPC-conference series truly unique: Connecting thought leaders, technology developers, and researchers with corporate entrepreneurs who put these strategies into practice. We organized the MCPC 2017 as a multitrack conference featuring a combination of high profile keynotes with expert talks, exhibitions, panel discussions, paper sessions, workshops, receptions, lab tours, and much more. Three hundred academics, entrepreneurs, and management experts co-created the conference with their active participation. Nearly 100 presentations, exhibitions, workshops, and tours were offered at the MCPC 2017.

All academic papers have been selected in a blind peer-review process, supervised by an advisory board of experienced experts in the field. The collection of articles presented in this volume comprise an overview of latest research from the worldwide MCPC community bringing together new thoughts and results from various academic disciplines within the areas of:

- Customization and personalization via smart products and smart services
- Digital manufacturing and Industrie 4.0
- Mass customization and sustainability
- Choice navigation and customer interactions for MCP
- Solution space development and variety management
- Mass customization of textiles and fashion products as a special field of application

We believe that this selection of articles represents the scope of perspectives on MCP, helping us to better understand the diversity and plurality of this topic. While a mass produced, hence standardized book on mass customization and personalization seems to be an oxymoron, we are very sure that you will develop your very own, individual perspective and "takeaways" from the research and experiences presented in this volume.

Aachen, Germany Stephan Hankammer
Aalborg, Denmark Kjeld Nielsen
Aachen, Germany Frank T. Piller
Aachen, Germany Günther Schuh
Aachen, Germany Ning Wang
Aachen, in January 2018

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About the Editors

Stephan Hankammer is a postdoctoral researcher at the Technology and Innovation Management Group at RWTH Aachen University. He studied Business Administration, European Studies and Philosophy at WWU Münster, University of Granada, Philipps-University Marburg and University of Sevilla. He received his Ph.D from RWTH Aachen University for his dissertation on customized and collaborative value creation from the perspective of sustainability. In 2016 he spent three months as a visiting researcher at Politecnico di Milano. He has been coordinator of a European ECO INNOVERA research project on sustainable mass customization in the consumer electronics industry. Moreover, he has worked on larger mass customization projects in several other industries in both B2C and B2B settings. In his research, Stephan Hankammer focuses on sustainability oriented innovation management, especially collaborative value creation, sustainable mass customization, and sustainable business models.

Kjeld Nielsen is an Associate Professor in the Department of Materials and Production at Aalborg University. Kjeld Nielsen is head of the Mass Customization Research Group. His research interests include mass customization, product configuration, reconfigurable manufacturing systems, and product architecture.

Frank T. Piller has headed the Technology and Innovation Management Group at RWTH Aachen University since 2007. Earlier, he worked at the MIT Sloan School of Management and was an Assistant Professor of Management at the TUM Business School (1999–2004). Frank Piller graduated with a Ph.D. in Operations Management from the University of Würzburg in 1999. His post-doctoral Habilitation degree is from the TUM Business School. Frank Piller has worked as a consultant and delivered executive workshops for many international companies, including several DAX30 and Fortune 500 corporations. As a member of their board of directors or board of scientific advisors, he works with a number of innovative technology companies to bring his research into practice. His current research focuses on the need of established corporations to cope with the challenge of digital transformation and similar disruptive technological innovations. This includes a growing stream of research on digital business models and the systematic design of platform-based business ecosystems, but also research on Leadership for Industrie 4.0 and the establishment of organizational structures and cultures that allow for change. He is the Chairman of a cross-industry group hosted by VDI (Verein Deutsche Ingenieure) to develop standards in the field of platform-based digital business models ("Fachausschuss Geschäftsmodelle für Industrie 4.0").

Günther Schuh is a German engineer and has held the Chair for Production Systems at the RWTH Aachen since 2002. He is also Director of the Research Institute for Rationalization, a member of the Board of Directors of the Machine Tool Laboratory (WZL) of RWTH Aachen University and the Fraunhofer Institute for Production Technology (IPT). A further academic task is the management of RWTH Aachen Campus GmbH. Since 2004, he has also been on the directorate of the Research Institute for Operations Management (FIR) at the RWTH. From 2008 to 2012, he was Vice-President for Industry and Economics of RWTH Aachen University. Prof. Schuh has additionally worked in several supervising and management boards.

Ning Wang is a research associate at the Technology and Innovation Management Group at the RWTH Aachen University since 2014. She conducts research in the area of mass customization and personalization, consumer co-creation, and user toolkits design. Her research tries to extend the conventional mass customization and personalization understanding from a new perspective: smart products for customized product services beyond the point of sales. She has been working on research projects of cross-cultural toolkits development for online customization, design parameters of the smart product-service system (Smart PSS) and how to achieve user-satisfied customization and data-driven service personalization via a new form of smart product and user interaction design.

The original version of this book was revised. An erratum to this book can be found at https://doi.org/10.1007/978-3-319-77556-2_44

Part I
Customization and Personalization via Smart Products and Smart Services

User-Centered Service Innovation for Commercial Vehicles: Plugging in the Handyman Market

Kate Spierings, Nicole Eikelenberg, Dirk Snelders, and Froukje Sleeswijk Visser

Abstract There is no vehicle segment where personalisation is as common, as for Light Commercial Vehicles. These vehicles are used for a large variety of tasks, supported by an ever-increasing number of new services. For Light Commercial Vehicles, one of the most interesting market segments from the perspective of service innovation and product personalisation is the handymen market. Handymen have a very strong relationship with their vehicle, highly specific mobility needs depending on their specialisation, and spend a lot of time personalising their vehicle.

This paper presents the Plugs concept. The Plugs concept is a new open-source approach to deliver personalised services for Commercial Vehicles to the handyman market. The concept was created based on user research and service innovation done by the TU Delft Design School in collaboration with Ford stakeholders from the Research and Innovation Center in Aachen. To deliver a broad variety of personalised hardware- and software-based services, called Plugs, to small handyman businesses in a cost-efficient way, Ford should build a strong open-source platform strategy around the core Ford Transit product, involving third-party developers and handyman lead users in the creation of these Plugs.

Keywords Service innovation · Light Commercial Vehicles · Handymen · Mass customisation · Open-source · Platform strategy · Plugs concept

1 Introduction

In one famous moment, Henry Ford said about the Ford model T, one of the first mass-produced consumer automobiles, that 'any customer can have the car painted any colour that he wants so long as it is black' [6]. As the automotive industry

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is challenged by trends like digitisation, access over ownership and environmental concerns [8, 13], this top-down approach of selling one car to all is no longer realistic, and the pressure to innovate is high. Instead, a focus on product tailoring and creating loyalty through service offerings and building long-term customer relationships is becoming increasingly important for automakers [13]. This means that at the same time, a switch from a focus on products to a focus on services or service innovation is necessary.

Automakers have started providing a broader variety of options that allow for the mass customisation of cars and vans. Mass customisation aims to deliver personalised products that answer real user needs, with the benefits of mass production for the provider of the goods or services in question [12].

In the automotive industry, mass customisation is still mainly achieved through assembly line production: a variety of product and service options are assembled around the core product that is manufactured on a moving production line, not too different from the original Ford model T production line. During this process, standard parts and subassemblies can be put together to make more ‘personalised’ offerings: common vehicle platforms and chassis are used, which can be chosen in a colour of preference and upfitted with certain automotive features or accessories, picked by the customer. Supply is created through upfront estimates of buyer preferences. Aftermarket services like maintenance contracts, in-car connectivity, car insurance and small adaptions to vehicles are provided through dealerships. And so, automakers can provide customers with more personalised vehicles.

There is no vehicle segment where personalisation is as important as for the Light Commercial Vehicles market. The Ford Transit range highlights this well, considering the Transit Custom alone comes in more than 5000 possible variations.

Light Commercial Vehicles are designed and constructed for the carriage of people and goods and have a maximum mass not exceeding 3.5 metric tons [5]. These vehicles are used by many different businesses and users for a large variety of tasks, in turn demanding an ever-increasing number of new product variations and services. Besides choice from a broad spectrum of automotive features, not only van exteriors but also complete van interiors are adapted through upfitting services to fit highly specific customer needs. Furthermore, a small range of special services is available like telematics, leases and maintenance. These services, however, are mainly focused on big fleets of vehicles, over smaller businesses. This means that the main beneficiaries of such services are also the fleet or business managers, over the end users of the vehicle. The Light Commercial Vehicle market, however, consists of many small market segments [1].

For Light Commercial Vehicles, one of the most interesting market segments from the perspective of service innovation and mass customisation is the handymen market. This is a user group that can be addressed through a limited set of marketing channels, whilst on the other hand, it has a very large variety in terms of specialisation and thus the needs and wishes for their van. Furthermore, research by the Freight Traffic Control of the city of London showed that more than 32% of all Light Commercial Vehicles in Britain in 2014 were accounted for by handymen businesses: small construction (plumbing, building, plastering and others) and electrician companies [1]. As such, handymen form a very interesting and big user group for service innovation around Light Commercial Vehicles.

Furthermore, many handyman businesses lease or buy their vans from the secondhand market via dealerships or auctions [1]. As such, handymen and handymen businesses are a very interesting group to provide services to that enable customisation of the vehicle, even if they are not the first-time user or owner of said vehicle.

The Ford Motor Company has a lot of experience in the field of traditional product innovation. The year 2016 was a record year in number of inventions that were disclosed by Ford employees. However, with the transformation from an auto to a mobility company, Ford is looking into opportunities where not only products play an important role but also services [8]. Service innovation is less well known inside Ford. To this intent, Ford has recently started collaborating with the design school at the Delft University of Technology (the faculty of Industrial Design Engineering) on the topic of service innovation for the Light Commercial Vehicle market [10]. The aim of this university research project was to come up with user-centred opportunities for service innovation based on research with end users.

Below, one such service opportunity is presented, as a demonstration of what service innovation can add to the ever-increasing customised and personalised offerings of mobility companies like Ford.

2 From User Insights to Service Opportunities

As a first step in this demonstration, insights were collected on the user profiles of handymen [9]. This has been done through contextmapping. Contextmapping is a generative Delft design method in which contextual research is done with real users to gain tacit knowledge about the context and current use of a product [15]. The contextmapping with handymen included shadowing, interviewing and the development of personas and user journey maps [9]. The results of the research were then analysed to find out what is important for this user group when it comes to their van and their handyman business and to discover differences between handyman niches.

The contextmapping was done with three different types of handymen working in small businesses: plumbers, electricians and carpenters. Of each niche two handymen were followed in their daily work. Some were employed handymen, others an independent handyman that owned their own business. An example user journey of a typical electrician's day and his tasks can be seen in Fig. 1.

Based on this first study, several directions were identified for interesting service innovations for handymen. The contextmapping research done by Hnatiuk [9] showed that there are many opportunities for mass customisation services to support the lives and livelihoods of handymen. To give some insight into interesting opportunities, the most important research findings are now presented [9].

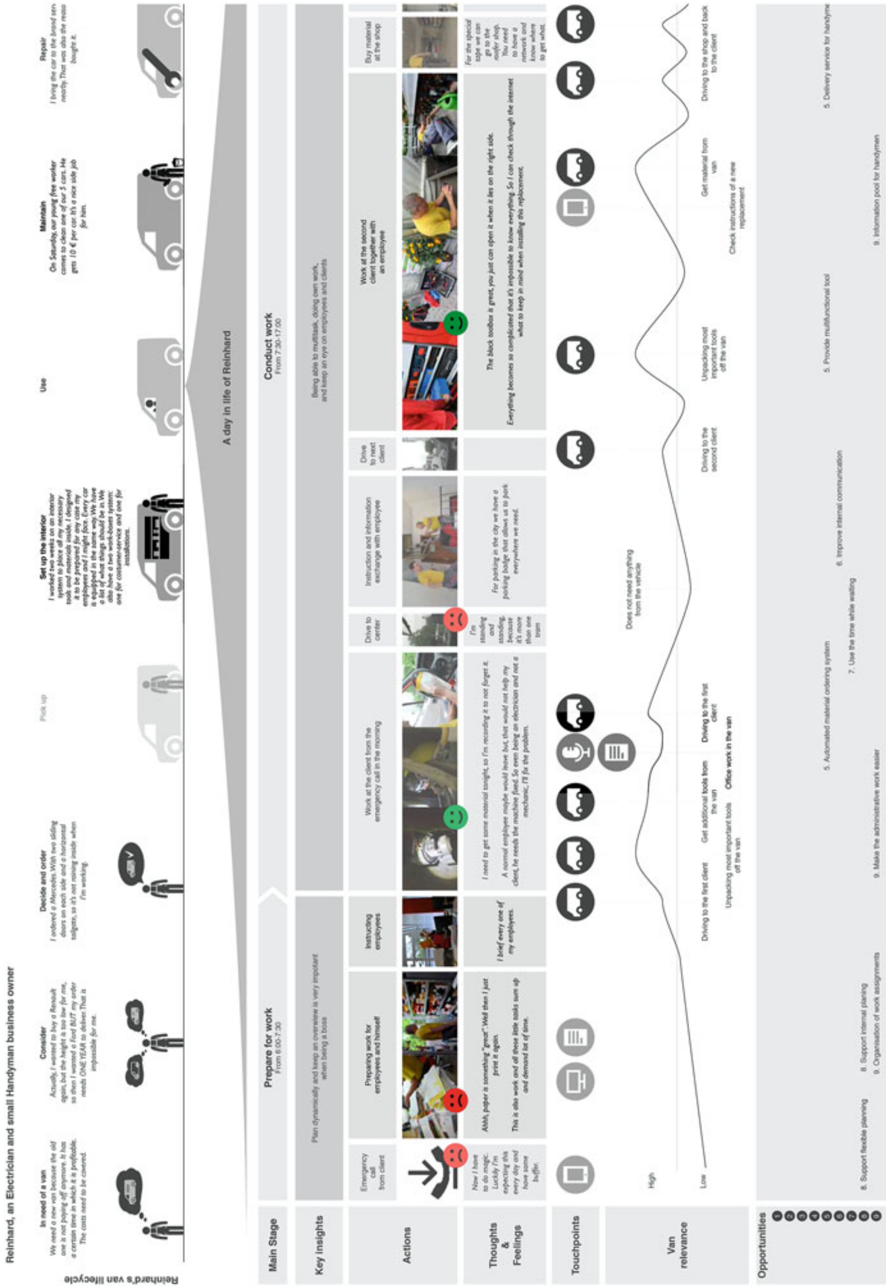

Fig. 1 User journey of a typical electrician working day (Source: Hnatiuk, 2016 [9])

Fig. 2 The different functions of a Handyman Commercial Vehicle (Source: Hnatiuk 2016 [9])

A handyman's van is not only a means to get from A to B; it is also a toolbox, office, lunchroom, stock room, business card and a source of professional pride and corporate identity (see Fig. 2). In short, handymen spend a lot of time in or in close proximity to their vans. Because of this handymen often tailor their vehicles to their needs and have a very strong relationship with their vehicle. Interiors are custom-made or chosen after a long period of scrutinising different options, to accommodate the different functions of the van throughout the day. Van exteriors are often adapted as well, for instance, with stickers, to display the handyman company information, or with roof racks to add more stock space. Therefore, supporting a flexible van set-up through mass customisation services that focus on tailoring and upfitting of existing vehicles is a key opportunity for automakers.

In addition, there are many opportunities for services that increase handymen business efficiency through connectivity and automation. Even though handymen are proud professionals that want to spend their time on their core job – building and repairing – they also want to stay in control of every aspect of their job and/or business. This means that throughout the day, they keep track of used materials, current inventory, working hours, driven kilometres and many other things themselves. This is often done by hand. At the end of the day, most handymen end up ordering new materials and stock themselves and spend copious amounts of time doing more bureaucratic tasks and desk work, like making invoices and receipts, and logging working hours. Herein lie many opportunities for mass customisation services around the digital aspect of the handyman business: automated tracking and processing of business information through a connection with the vehicle. An example of this could be to automatically track and process the driven kilometres and support an easy connection between the collected vehicle data and the handyman back office. As every handyman business uses different software or systems for their management processes, a wide range of tools would need to be supported.

One of the main outcomes of the collaborative sessions was that there is an enormous potential for the aforementioned connected services that help to improve handyman business efficiency. All of these services, however, require a certain infrastructure and connection to the vehicle and/or to vehicle data. This led to the insight that there is a need for an infrastructure that enables services and smart hardware to be 'plugged into' the vehicle and for a new strategy to enable the mass customisation of Light Commercial Vehicle services – and so the Plugs concept was born.

Employees from Ford England and Ford Germany and professors and researchers from the TU Delft closely collaborated to further analyse and elaborate on the Plugs concept in several design and prototyping sessions, using different ideation and storyboarding techniques. The main tool used for ideation and storyboarding was the Scenes tool, designed by SAP [14]. Furthermore, literature research and studies of existing similar innovations in different domains were done to identify best practices, which will be discussed in the next section of this paper.

3 Mass Customisation for Commercial Vehicles: The Plugs Concept

The Plugs concept consists of a special Commercial Vehicle design that provides an infrastructure inside the vehicle, to which both software and hardware can 'connect'. This means that the infrastructure provides both a data network and a power network throughout the vehicle.

Third parties can then deliver singular software or hardware solutions to the handyman end user through the Plugs marketplace. A schematic overview of the value exchange between stakeholders can be seen in Fig. 3. The Plugs concept could thus be compared to what an app store is to a smartphone. Users can choose different add-ons, called Plugs, to personalise their Commercial Vehicle. Through a combination of smart hardware and software Plugs, live (vehicle) data can be used to automate, track or help with the aforementioned tasks and problems that the handyman runs into during the day around his van-based business.

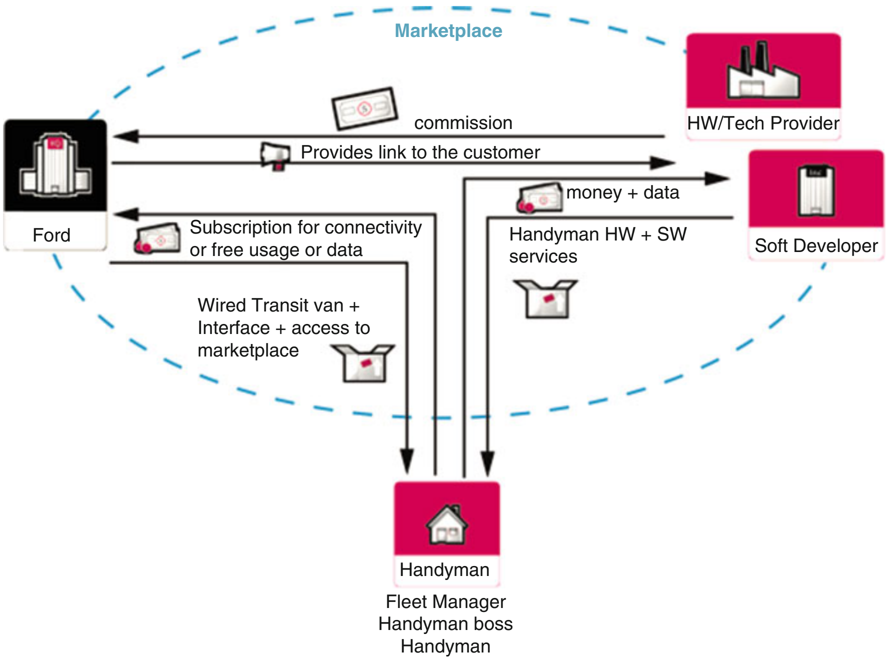

Fig. 3 An overview of the value exchange between involved stakeholders in the Plugs marketplace (Source: Spierings 2017 [16])

The Plugs concept is backed up by a platform strategy, in which Ford, the automaker, focusses on the core product, and other parties can provide smaller software- and hardware-based services, known as Plugs, around this core product through a development platform. The existence of many Plugs will lead to a higher value of the core product.

3.1 Involving Third Parties in the Plugs Concept

To successfully build Plugs vehicles, Ford would need to fulfil certain capabilities that are required when developing mass customisable products and/or services. This is to provide 'the capability to manufacture a relatively high volume of options for a relatively large market (or collection of niche markets) that demands customisation, without tradeoffs in cost, delivery and quality' [12]. Logically, then this creates the need to involve other parties, like technology start-ups and software developers, to make for more efficient production.

Together with Ford RIC stakeholders, three main benefits in involving third parties to create the Plugs concept were identified:

1. Cost and quality effectiveness: each partner/developer works on features in their area of expertise, leading to higher cost effectiveness in terms of R&D and supply chain, and a higher quality of the partial solutions that are offered as they have been created by domain experts.
2. Higher speed of innovation possible: many small solutions and connected features can become available with a shorter time to market, as many features can be developed at the same time by different parties who already have expert knowledge on a topic. This will also lead to a high level of variation in the features.
3. Democratisation of new Commercial Vehicle technologies: in the case of big automotive OEMs, low cost effectiveness and low economic viability of working on services for small user groups mean that services are usually created for big fleet clients or big generalisable user groups. By creating an open platform, connected solutions would be available for smaller Transit user groups and niche markets that would otherwise be overlooked. In the case of Ford, this democratisation also fits well with Ford's brand image of accessibility and affordability: making mobility available to all.

To work together with third parties, the only feasible approach would be to open up certain company boundaries, to enable the inflow of outside knowledge and contributions from other parties and domains, defined as open innovation [3]. The next section of this paper explores how to create a successful open innovation method around the Plugs concept to achieve high-quality, user-centred and economically viable Plugs services.

3.2 Creating an Open Platform Around the Plugs Concept

Three business scenarios were created to explore possible innovation models around the Plugs platform, with the aforementioned storyboarding tool Scenes:

1. A closed supplier relationship in which Ford outsources the creation of previously defined services to third parties
2. A cocreation partnership in which Ford works together with third parties to create innovative new services and
3. An online community-led open-source platform in which third parties are free to develop Plugs for Commercial Vehicle users

In sessions with Ford employees, the different storyboards were evaluated, and the third scenario, an open-source platform, was chosen for further development.

Given the potential value of the Plugs concept and the hesitance that resides around open innovation in the automotive sector, the big question then is: how can Ford set up a platform where third-party developers will start and continue to provide useful Plugs to handymen, whilst overcoming open innovation barriers and typical pitfalls in open-source projects?

A broad study of Ford OpenXC, the iOs app store and literature on open-source development lead to insights on the failure of Open-Source development platforms.

Ford has some experience with open-source projects. An interesting previous innovation is OpenXC. OpenXC is an open-source hardware and software platform that enables the extension of the use of vehicle data beyond common vehicle diagnostic purposes, as live vehicle data can be used as input for self-built apps [7]. To access this vehicle data, an OBD-ll plug can be used that uses a software module to enable the extracting, reading and usage of live data from the vehicle [7]. Users of OpenXC can then incorporate vehicle data in their apps or products to provide extra functionality. Examples of vehicle data that are available through OpenXC include driving speed, engine information and brake information [7].

As it appeared through research with Ford stakeholders, OpenXC is not used that much by external communities or for commercial purposes. It is mainly used as an internal Ford research tool for new automotive features and in the external environment amongst a select group of automotive university researchers. Reasons for low adoption are the limited sets of vehicle data available, difficulties in getting to know the OpenXC platform and its possibilities online and the small range of cars and thus users that can be targeted with OpenXC.

Apple's approach to open-source service development is quite different. The iOS app store provides clear developer documentation online and heavily shapes the development process through strict guidelines for developer's apps and mandatory tools, hand-in formats and programming languages. However, this approach can also form a high barrier to entry for new developers due to the level of time needed to get started and the limited freedom developers have.

Literature research further underlined typical reasons for failure of open-source projects [4]. All research results have been summarised below.

Open-source platforms often fail due to the following reasons:

- Failure related to product security:
  - In the automotive industry, open standards and open software mean that the CAN bus, the control system of the car and/or certain vehicle data becomes available or accessible. This poses risks for the hacking of vehicles, something automakers want to avoid at all costs.
  - In open-source development, the lines of who built certain software or hardware are blurred, as it is built on creative common principles that any information can be adapted by any active participant of the community and returned to this community for the benefit of the end product [4]. Software or hardware solutions are thus often cocreated or coevolved, which can lead to IP issues and tangled ownership of contributions [4].
- Failure related to business strategy:
  - Many open-source projects fail because there is no clear revenue or business model behind the project. In commercial open innovation projects, it is highly important that all stakeholders gain from their contributions and work towards the same goal [4, 11].

  - Marketing can also become a reason for failure in open-source environments as development thrives when there is a big and active community. Great open-source propositions can fail if the benefits of participating in the project are unclear, or it is difficult for potential developers to join, as research into OpenXC demonstrated [7]. Attracting users and developers to the open-source product or platform is very important for success [4].

- Failure related to a lack of participation:
  - Open-source projects can fail when there is no real user or developer need for the core product or service around which the project evolves [2, 4]. This is often the case with a lack of market or end-user understanding [2, 4].
  - A lack of a vibrant user and/or developer community is one of the biggest causes for failure in open-source projects, as the absence of a strong group of users makes it unattractive for developers to participate in the project and vice versa. This phenomenon is known as a network externality. Network externalities come to play in two-sided systems, where the value of the system increases or decreases with the amount of end users, on the one side, and services, products or developers on the other side [11].

3.3 Overcoming Open-Source Challenges

To be successful, the Plugs concept needs to overcome the abovementioned challenges.

Overcoming Product Security Challenges For Ford a certain level of secrecy and security can be maintained by using Application Programming Interfaces (APIs) to establish which vehicle functionalities are opened up to developers for the creation of applications and products. For third parties that want to contribute to the Plugs platform, clear guidelines and rules around intellectual property of Plugs and access to the vehicle will be needed. It will be more attractive for third parties to participate and contribute if they maintain the rights to their own Plug and get a broad level of access as not to block third-party creativity and allow for more innovative Plugs.

A way for Ford to create clear guidelines on the terms of collaboration could be through a membership contract, IP Policy and/or EULA (end-user license agreement), as is common in open-source software settings.

All Plugs should be quality-controlled by Ford in terms of vehicle security and user data privacy to make sure that security of solutions goes both ways, for the developer and the handyman end user.

Overcoming Business Strategy Challenges Plugs should provide valuable solutions to real user needs or problems, to create a vibrant community of handyman end users. Close collaboration between the different stakeholders during the development and implementation phase of the Plugs platform is important to establish a strong benefit for each stakeholder involved. Different business and revenue models would also need to be explored.

Furthermore, strong marketing is needed to attract both developers and end users. This could be done in the form of initial Plugs showcases. From a user perspective, it is important to highlight the advantages of a Plugs Commercial Vehicle: a more efficient and pleasant handyman business. For developers it is important to provide correct and good APIs and documentation, to make it easy to get started with the development of Plugs by providing all necessary information and to link to the end-user group. To make sure developers and the handyman can connect well, a mediating layer of lead developers is needed on the development platform to aid in communication. These lead developers can also provide support to developers during the creation of Plugs.

Overcoming Participation Challenges Attracting initial Handyman users and third-party developers to the platform is the most important step for the implementation of the Plugs concept. Before launch a certain amount of ready and attractive Plugs should be available to attract handyman users. In turn there should be a strong incentive for third-party developers to join the Plugs platform, to create a vibrant community of developers. This can be done by showing the interest of the end-user group, underlining the vast amount of Transit users, making the creation of Plugs easy through clear documentation and APIs and offering clear monetisation options for the use of Plugs.

Through network externalities, the presence of a big developer group will lead to a higher interest of the end-user group and vice versa [11]. So, the Plugs platform will continuously increase in value once it has more developers, users and Plugs.

3.4 Facilitating an Open-Source Development Process

The proposed approach to create a successful open platform is to involve handymen and third-party developers in the complete development process of creating, testing and commercialising Plugs in a Ford-regulated process with clear guidelines.

In the first phase, the problems and challenges handymen are facing can be used as a starting point to attract developers and create showcase services to pre-populate the Plugs marketplace. With many Plugs add-ons available, it will be more attractive for handyman users to adopt the new Plugs vehicle. A lead user group of handymen, as well as third-party developers, can then be invited into a community to discuss and explore needs and challenges together. The lead user group, called the 100, consists of Ford Transit users that have been picked for their profile.

In a second phase, once ideas for apps and add-ons are to be prototyped, the handymen 100 community can be involved in (beta)testing prototypes and can provide (direct) feedback to third parties, which should be mediated by a group of lead developers that are also handyman domain experts, with previous experience

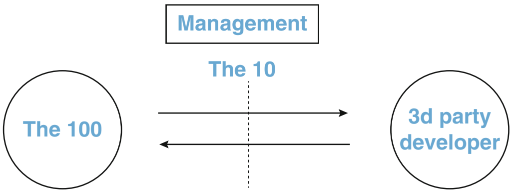

Fig. 4 Overview of the collaboration model between stakeholders on the open-source Plugs development platform (Source: Spierings, 2017)

of building Plugs. This group of lead developers, called the 10, is to be scouted and employed by Ford.

In the third phase, the commercialisation phase, Plugs are offered to the Light Commercial Vehicle user community through the Plugs marketplace, and every handyman can use them to personalise his or her van.

Meanwhile, as the Plugs platform matures, it should become increasingly more open to the broader public: any interested user or developer should then be able to participate in the development of new Plugs for the Ford Transit. Finally this will lead to the collaboration model as shown in Fig. 4, where a Ford management team monitors the overall platform success and steers the platform strategy; where third-party developers create novel services, in collaboration with the 100 handyman lead users; and where the 10 lead developers, employed by Ford, moderate the connection between the handyman lead users and third-party developers and control the security and quality of new Plugs [2].

4 Conclusion

The best way forward to offer mass customisation services to the Commercial Vehicle market is to create an open platform on which multiple parties can come together to create services: end users, third-party software developers and start-ups and automotive OEMs. There is no other cost- and/or resource-effective way to offer a broad variety of personalised high-quality services to smaller businesses and user groups, like in the handyman market. However, for an automotive company like Ford, developing an open platform is controversial.

To be successful in offering useful Plugs, it is important to attract a large developer and user community that can easily link to each other to create novel services. This is most feasible through an open innovation platform.

Involvement and interest of the target group of handymen on the Plugs platform are expected to be the most important success factor, as this will attract third-party developers to contribute and develop services, create the basis for a viable business and revenue model and lead to Plugs services that provide value to the end user.

Ford can focus on the core product – the Ford Transit – and the vehicle's special electrical set-up whilst applying a platform strategy. Third-party developers and end users themselves, who are domain experts, are then invited to develop features and value-added services for the Transit.

5 Discussion and Implications

To become a market leader after introduction of the Plugs platform, a future strategy could be to drive open innovation in the Commercial Vehicle market even further. However, some organisational barriers may make it hard to do so.

Driving Open Innovation by Eliminating Customer Lock-In One way to increase attractiveness for third-party developers and end users to join the Plugs platform could be to remove lock-in effects. In the automotive sector, vehicle standards are bound in secrecy and incompatibility. By opening up the vehicle system and providing an open standard, platform fragmentation between new models and/or brands could be eliminated. For users this would mean that they could use certain Plugs, even if they do not own a Ford Transit. For developers this would mean that their potential user group grows vastly, which would make it significantly more interesting to create car-specific Plugs or 'apps'. This strategy, however, would be highly controversial in the automotive sector.

Challenges for Adoption of Open-Source Projects Within Ford As the Plugs concept is built around an open platform, it is also important to overcome certain internal company challenges during implementation. It is advised to start a separate business unit for the Plugs platform, to maintain a certain distance from standard automotive innovation processes that can be highly monitored, arduous and slow. It will be important to maintain a strong link between separate business units to feed back valuable learnings on Commercial Vehicle usage to the Ford mother organisation.

Partially opening up the vehicle to third-party developers could lead to resistance from the Ford internal community or not-created-here syndrome. Furthermore, a new separate business unit could be received with great scepticism by internal stakeholders.

Evaluating Platform Success Another challenge is the perception of the platform's success: Ford should make sure the Plugs platform does not get evaluated in the same way as running projects or current car models. The separate Plugs business unit should perform as a start-up and should use new and different KPIs to measure the success of the Plugs platform. Evaluation should avoid quantitative metrics like direct and immediate profit made through the Plugs platform but focus rather on the creation of business value with the new open innovation approach.

For Ford one such example of created business value is that the Plugs platform would be an insightful way to learn more about its Commercial Vehicle users and their use of the vehicle and existing services. This knowledge could then be used to design better future Commercial Vehicles and mobility services, targeted at end users.

Remaining in Control A certain level of control over the actions of third-party developers, the suppliers of Plugs, would be mandatory to fit with Ford's strategy and vision.

Maintaining an in-vehicle Ford user experience towards users is important in the current automotive market. To make sure that happens, guidelines for potential user interactions and interfaces – still to be designed – could be used.

Besides APIs and contracts or agreements, proper moderation of the online community on the Plugs development platform is also necessary [2]. Lead developers, the 10, employed by Ford could also filter out irrelevant contributions, potentially steer the development of certain Plugs to make new innovations more valuable from a Ford perspective and even scout for popular services to professionalise them in future Ford Commercial Vehicles. However, these things should be done very carefully as not to scare away potential developers or cannibalise Ford's own business.

Contribution of This Project and Further Development of the Concept The Plugs platform would make a broad range of telematics services, automotive features and connected services available to and centred around the end users of Commercial Vehicles. Currently, connected services are targeted mainly at fleet or business managers and focussed on staying in control of operations and on monitoring driver's behaviour and their performance. However, contextmapping research with handymen has shown that there are many benefits for end users of Commercial Vehicles to be gained as well, through connected services.

As automotive companies are shifting from a product to a servitisation approach, the creation of long-lasting relationships with customers is increasingly important. Therefore, it is important to also shift away from an automotive sales and after-sales perspective to a perspective of providing value to users over the complete lifetime of their vehicle. The Plugs platform would help to provide this value to the end users of Commercial Vehicles by offering a standardised vehicle that can be upgraded with new quality automotive features and connected services at any moment.

For successful implementation of the Plugs platform, further development and a trial should be run on how to collaborate with third parties and how to set up the open platform in a way that is beneficial for all stakeholders involved. For a trial it would be interesting to involve start-ups with new technologies to gain insight into the necessary information and guidance needed to create successful Plugs and to involve handyman businesses to gain further insight into end-user needs.

After an initial trial and introduction for the handyman market, the Plugs platform could be expanded to different Commercial Vehicle niche markets and mobility domains. In the future personalisation options could then be provided for different van-based professions, ride-sharing services, autonomous vehicles or passenger cars.

With an increasing complexity in user needs, the need for open innovation, partnerships and open standards in the automotive sector is growing. Furthermore, automakers need to gain more experience in service innovation, through trial-and-error and switching to a user-centred development process. For Ford, the Plugs platform could be a first step in that direction.

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Design for Mass Individualisation: Introducing Networked Innovation Approach

Ravi K. Sikhwal and Peter R. N. Childs

Abstract This paper outlines a nascent field of product innovation, which we believe will become significantly more relevant in the near future. Product design for mass individualisation is a new product design paradigm that comprises an open hardware platform and multiple modules that are integrated with the platform. It gives freedom to end users to integrate different modules into the platform as per their choice. Large manufacturers will produce the platform and some specific modules. Other modules will be invented and produced by smaller companies and by the user. This type of product integration will be engaged with by the all actors involved in the design and aims to help them to be more creative and innovative. Strategic and technological integration of all these actors, which is also the theme of Innovation 4.0, is the main focus of this work to intensify the innovation. Key areas which need to be focused on are identified and presented by an explorative study of existing product design and customisation approaches. Based on the explorative literature analysis, an industrial questionnaire survey has been conducted, and results are presented for the industrial implication and insights on this approach. The findings clearly show that the end product from product design for mass individualisation will be more creative and innovative.

Keywords Mass customisation · Mass individualisation · Product design

1 Introduction

The need to innovate products has become so intense that traditional product design and development processes cannot fulfil the requirements. Innovation in terms of product or process is one of the key concepts to address this issue. A new product

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design paradigm which could serve the need of adaptability, upgradability and sustainability and meets the exact requirement of the end user has the potential to fulfil this demand.

Traditionally, most products are designed by professionals working for the underlying firms in design teams because those people ‘have acquired skills and capabilities that allow them to perform most design tasks more effectively and at a higher level of quality’ [1]. However, product design paradigms have changed significantly over time, led by technological advancement. Innovation technologies (IvT) [2] have facilitated new strategies for product design and development.

This paper aims to investigate the role of innovation in the product design process with the theme of networked innovation. The basis for the approach to networked innovation is the industrial practice of open innovation. Open innovation is defined as the use of purposive inflows and outflows of knowledge to accelerate innovation and expand the market for external use of innovation, respectively [3]. The advantages and disadvantages of different forms of openness in firms have also been investigated in recent research on open innovation. Dahlander and Gann [4] studied the influence of this openness on a firm’s ability to innovate and appropriate benefits of innovation. However, this kind of engagement between internal and external actors for innovation process requires multidirectional management and strategic integration. The latest practice of Innovation 4.0 addresses this complexity in open innovation.

2 Product Customisation

The concept of industrial product design has changed significantly over time, from individually crafted designs to product design for mass production (MP), followed by product design for mass customisation (MC). These changes are always triggered either by market conditions or the consumers’ desire for the product offering.

2.1 Customisation Concepts

Up until the industrial revolution, products were designed and made by craftsmen with a localised design stretching back generations. The concepts and processes associated with MP revolutionised the way products were designed and manufactured. Technological advancement later made it possible to design and manufacture products in mass quantities more quickly and cheaply. This is usually attributed to the early twentieth-century industrialist Henry Ford. His assembly-line approach to the manufacturing of the Model T motor car reduced the cost of the vehicles to such an extent that they could be afforded by ordinary working people. The impact on the market, and therefore on product design, was revolutionary. As society’s desire to have a variety of similar products to choose from started to change, companies introduced the concept of product design for MC by offering them different variants of the same product. Although MC offers variants of the same product, often the constrained availability of options limits the fulfilment of the need of the end user since variants are provided by the manufacturer itself with few actual changes in design.

2.2 User-Centered Customisation

An emerging literature stream posits that inclusion of users, rather than internal designers in new product creation, may benefit organisations because it results in a product which effectively satisfies consumer needs. Current product life cycle considerations from product conception, design, development, delivery, usage, service and end of life disposal have not been able to consider customers as individuals.

New technologies have democratized the tools for both invention and production [5]. Anyone with an idea can use advanced and accessible technology and turn it into a product. The user has started to contribute to the design process in parallel to the professional design teams. That certain users are able and motivated enough to innovate and are willing to share their ideas with firms is not new and has been documented extensively [6]. By considering customers as both individuals and as an integral part of the design process, implicit characteristics such as personal taste, traits, innate needs and experience become important integral parts of product design [7]. But recent changes in user aspirations and inclination towards more individualised product offering have motivated innovators and product designers to approach a new paradigm. The continuously increased aspiration level of customers and the growing saturation of the markets are the main drivers for the development of customer individualised products [8]. Kumar [9] has documented the strategic transformation from mass customisation to mass personalization.

2.3 Product Design for Mass Individualisation

Figure 1 shows the transition of manufacturing in the last 100 years. The volume of each product variant is decreasing from MP to MI. At the same time, product variety is increasing, showing the demand for more individualised products. It tends to reach a situation of market to one. Only the open platform-type product architecture can address this demand and will be able to realise this paradigm shift. Initial research on this paradigm shift has been carried out by Koren, Hu [10], but to realise this approach and to convert it into industrial practice, much more research need to be undertaken.

In the last few years, a demand for renewed product personalisation to satisfy the exact need of the customers has been observed in the market. Koren, Hu [10]

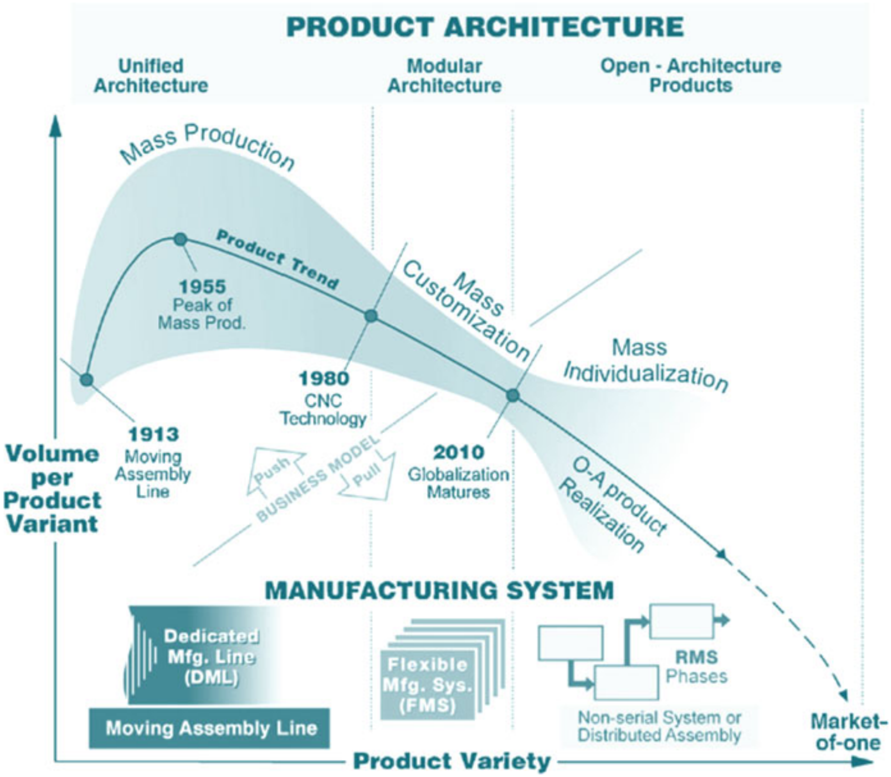


Fig. 1 Emergence of product individualisation [11]

has named this concept *mass individualisation (MI)*, a new paradigm for industrial product design. MI is based on the open platform product architecture that is mass produced by large manufacturers and multiple independent modules provided by other smaller companies and the end user. In product design for MI, the final product is the end result of the creativity and innovation of various actors, including smaller companies, large original equipment manufacturer (OEM) and end users. The open platform is integrated with different modules as per customer's need and is selected using the interactive design programme. Thus the end product, which fits the exact requirements of the customer, is highly individualised. Figure 2 shows the MI ecosystem with all of its actors actively involved in product design and development.

The product design for MI provides considerable incentive for the role of innovation. The future practice of *Innovation 4.0*, based on the strategy of 'open innovation' first suggested by Henry Chesbrough [12], provides a potential innovation practice for MI. Innovation 4.0 focuses on the strategic and technological integration of various aspects of innovation [13], focusing more on inclusive innovation rather than open innovation. It places the emphasis on the networking of all the areas of innovation, i.e. strategy and methods, technology and products,

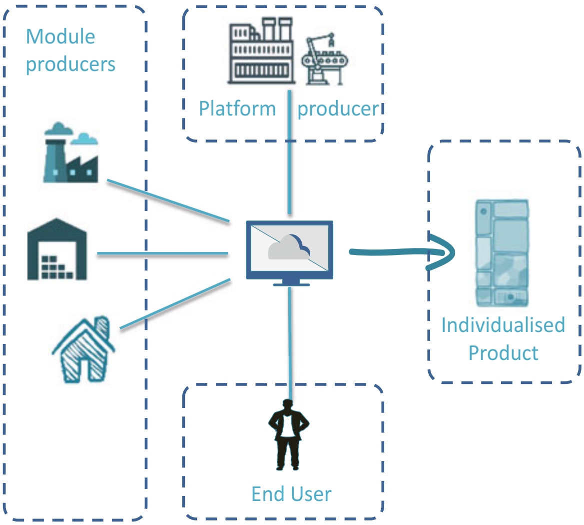


Fig. 2 MI ecosystem

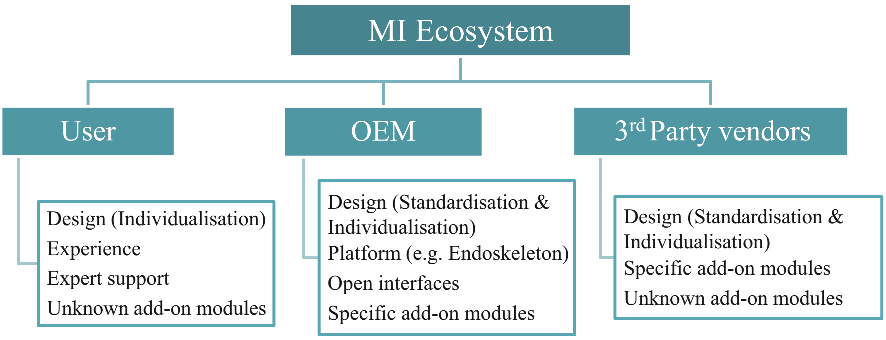


Fig. 3 Roles of different actors in MI ecosystem

processes and organization, society, communication and culture [14]. Connectivity becomes the central feature in Innovation 4.0. Everybody and everything need to be networked. By linking all the steps in the value chain, a world of possibilities opens for companies and other actors. Interactive models that are interconnected with institutions and individuals which develop, test and distribute new practices and artefacts via interactive processes need to be developed. This paper investigates the role and future prospects of networked innovation in product design for MI.

Product design for MI has the potential to create many new jobs in module production companies. End user's purchase intention and willingness to buy products will be enhanced with this product design paradigm. MI has the potential to address some of the challenges faced by the world today, such as diminishing natural resources, energy efficiency, demographic change, etc. Figure 3 summarises the roles of different actors in MI ecosystem.

3 Methodology

The cross connection between different actors involved in the design process of MI requires new creative and innovative approaches. It requires changes in the way traditional product design and innovation are approached. This section explains the used research design and applied methods, to understand MI and its industrial implications.

3.1 Overview of the Research Methodology

As described in the previous sections, Product design for MI is a relatively new and visionary concept. In the absence of existing applications, experimental research or case studies cannot be applied. Thus, to answer the research question in this uncertain context, only an explorative study of existing literature and practical feedback from industry practitioners and experts allows the derivation of valid conclusions. Therefore, the research methodology combines a qualitative exploration and quantitative analysis.

For a better understanding of this new paradigm, this paper aims to identify the key areas which need to be focused on to convert Product design for MI into an industrial practice. Across many industrial sectors, the end product will be far more efficient, effective, reliable, reusable and more fully utilized, with conservation of scarce natural resources such as energy, water and raw materials. An explorative study of existing product design and customisation approaches has been conducted; some of them have been included in the last section. Keeping Innovation 4.0 as a central theme, different areas and components of MI that need to be focused on are categorized into three categories:

1. Changes in traditional product design and customisation approaches that need to be focused on
2. Components that need to be focused on
3. Technologies that need to be integrated

Based on the explorative study, an industrial questionnaire survey has been designed. The findings of this survey were then descriptively analysed and interpreted for industrial implication.

3.2 Industrial Questionnaire Survey

The products from MI offer a rich, new set of value creation and innovation opportunities. A web-based industrial survey constituting multiple choice answers and text answers questionnaire were developed, based on the explorative study of related literature and existing product customisation approaches. Following the qualitative exploration of literature, the questionnaire was structured in the following three sections:

- Product design for mass individualisation (MI)
- Strategical and technological integration
- Practical suggestions

Most of the multiple choice question responses were measured using a categorical scale, with a provision of providing additional comments. The scale used five categories so that middle one represents a neutral stand point with different levels of agreement and disagreement on both sides. Appendix I shows all the questions, identified for the questionnaire survey.

Consumer product design companies (350 companies) across the globe were invited to participate in this survey via invitation email. Figure 4 shows the industry splits of the survey participants. Before sending invitations to participants, a pretest was conducted on the questionnaire with participants familiar with the topic, and feedback was used to improve and adapt the questionnaire accordingly. Responses have been recorded and then descriptively analysed to present the industrial insights and implication on key areas of this approach. This will be used to develop the approach further with practical implications.

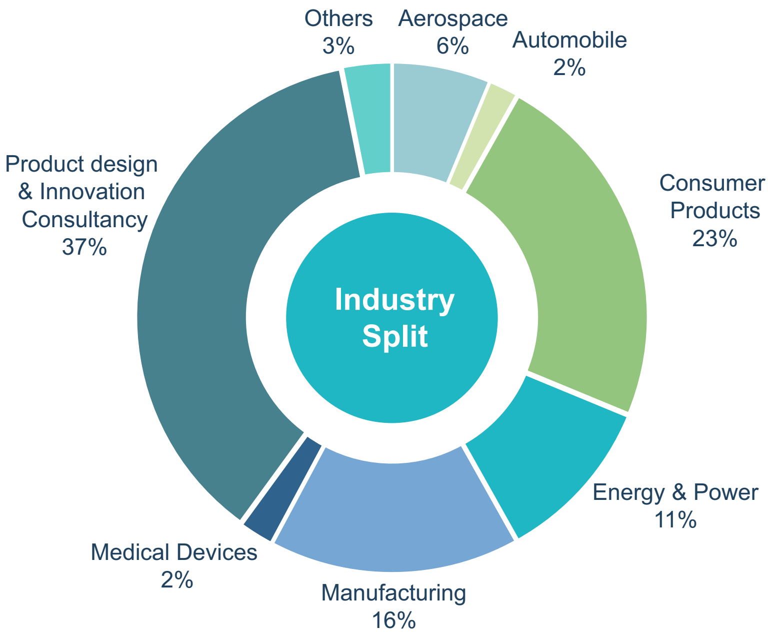


Fig. 4 Industry split of the questionnaire survey respondents

Table 1 Key areas and components identified to be considered for industrial implication

Changes in traditional product design and customisation approaches	Components that need to be focused on	Technologies that need to be integrated
Context	Design and development	Data mining
Ecosystem	Manufacturing	Innovation toolkit
Perspective	Assembly	Modelling
Vendor	After service	Product realization
Discipline	Sustainability, adaptability and upgradability	
Competition		
Access		

4 Results and Discussion

The explorative study of existing product design and customisation approaches identified different key areas and components to be considered for industrial implication. Table 1 summarises the findings of this explorative analysis.

Fifty responses have been recorded and analysed to present the industrial implication and insights on key areas of this approach. Appendix I summarises the responses along with the survey questions. Responses to these questions yielded a sufficient amount of relevant information about the product design of MI. The following sections present the discussion and insights obtained from these results.

4.1 Changes in Traditional Product Design and Customisation Approaches that Need to Be Focused on

The explorative study of existing product design and customisation approaches, identified changes in Context, Ecosystem, Perspective, Vendor, Discipline, Competition and Access.

Unlike traditional approaches to product design, MI consists of horizontal networking between different actors. The end product is the end result of the creativity of different actors. In MI, there are three main actors: end users, large companies, and smaller companies (includes third-party supplier, independent developers, etc.). Different actors could be mapped in a multi-level cross connected framework to simplify and manage the relationship between them. The inclusion of the wide variety of vendors in all aspects of the final product helps to intensify the innovation in the process.

Excellence through the interdisciplinary network is the main theme of this paradigm. Highly complex, socio-technical systems need to be developed which will require the collaboration of various academic disciplines. To realise the approach, future engineers needs to look beyond their own specialisation. A healthy competition between different actors needs to be encouraged for better design and innovation. The traditional approach of the close access need to be changed as networking of all the actors has to be backed by access to all essential information.

4.2 Components that Need to Be Focused on

The explorative study identified design and development, manufacturing, assembly, after service, sustainability, adaptability and upgradability as the design components which need to be focused on.

In MI the end user plays an active role in the design process. With the help of an interactive design platform, the end user selects the modules on the platform and designs the final product. This work has identified that it will be an iterative process as an end user will select modules on the platform and will then with the help of an optimisation tool make the end product more feasible and efficient within smaller companies and large manufacturer's constraints. Platform, interfaces and modules are to be manufactured at different places by different actors. Platforms are manufactured by large companies with interfaces which could be mechanical, electrical and software. This type of manufacturing needs advanced reconfigurable manufacturing systems (RMS) which can produce a variety of products with the same equipment and accessories.

A new networked assembly system needs to be developed which can assemble different components on the same type of platforms as per end user requirements. Smaller companies from different regions of the world will provide modules as requested and then the final product will be assembled at platform manufacturer. This paradigm will change the traditional way of after service. A new station or place has to be developed where platform manufacturer can connect users to module providers and provide the appropriate services. One of the key advantages of this new product paradigm is the contribution to the circular economy. As the final product is highly individualised, so it reduces overproduction of the products. Users can use the product for a longer time as it is exactly as per the requirements. Users can change the modules whenever they want. They can upgrade the products just by changing the updated module rather than changing the whole product.

4.3 Technologies that Need to Be Integrated

The explorative study of existing product design and customisation approaches, identified the following technologies that need to be focused on: data mining, innovation, toolkit, modelling and product realization.

Real-time connectivity and fast processing of data are some of the key processors to enable and realise this new paradigm. Internet-based innovation intermediaries can help to link different vendors and end user or large manufacturers. Any number of innovators and designers are able to collaborate to achieve innovative solutions. Access to research data and users' demand pattern are accelerators to the networked innovation process. A new strategic approach has to be developed for optimised use of data-mining resources. Innovation toolkits provide a way to transfer design capability to the end user. Users can use this kind of toolkit to enhance their understanding of different product scenarios, i.e. Web learning can be used to educate users in some specialisation needed for the personalised design. In this way, the user can put forward their latent needs which are not possible by conventional user research tools. A new networked innovation toolkit could be developed which can ensure that completed design can be produced on the intended production systems.

Simulation and modelling will be a very important part of this product design process. The objective of this system is to provide a platform for experimenting with products in the design phase. It allows the product to be represented, analysed and redesigned without going to physical prototypes. A new type of modelling tool which provides a platform for all the actors to access the design and receive feedback needs to be developed. Rapid prototyping and 3D printing are some enablers to realise the product before the final production. However, to realise products from MI, development of a new product realisation tool is required where the end user has all the freedom to experience the product and to provide live feedback on that experience to third-party module manufacturers or platform manufacturers.

4.4 Industrial Questionnaire Survey

Based on the explorative study and identification of key areas and components, described in the previous sections, a survey was conducted. The responses of this survey shown in Appendix I have been descriptively analysed for industrial implication and practical insights. First five questions were designed to obtain feedback on the existing knowledge and the importance of the new and innovative product design approach. Responses to Q.1 show that familiarity with the product design for MI is very limited in the industry. It is evident from these responses that MI is a relatively new product design approach and a lot of research needs to be undertaken in this domain. This paper is a small effort in that direction. Responses to Q.2 indicate that a maximum number of the responses came from consumer electronics companies. This agrees with assumptions mentioned in the earlier sections that consumer electronics products could be the starting point for the application of the product design for MI in the market. Responses to Q.3 are encouraging and in the line with the aim of this paper that MI would result in more innovative end products which will be tailored to the users' exact needs. Responses to Q.4 provide mix agreement. It could be interpreted in the way that certain segments of the market will consider MI as more favourable, probably

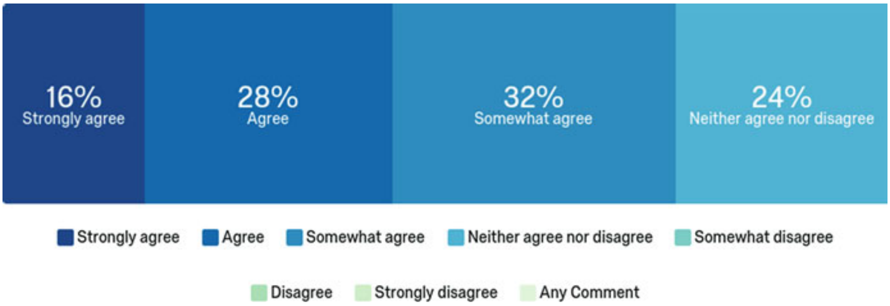


Fig. 5 Responses to Q.6, 'Product design for MI encourages creativity and innovation . . . '

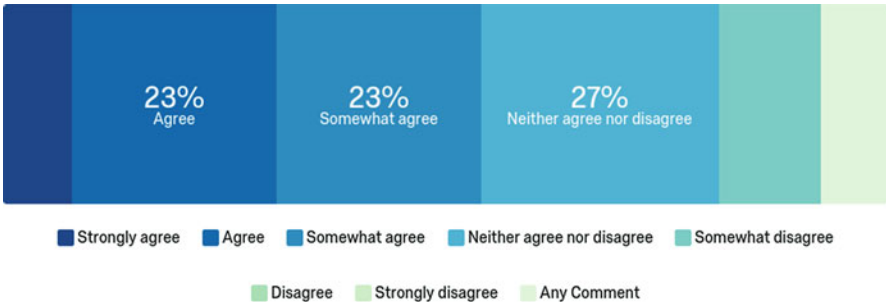


Fig. 6 Responses to Q.9, 'This product design paradigm also . . . '

consumer electronics companies as shown in the response of the Q.2. Responses to Q.5 provide an indication of the application of this approach to industry type. Twenty-seven percent of responses considered that the product design for MI is suitable for all industry types, but a surprisingly equal percentage of responses suggested the fashion industry as one of the main beneficiaries of this approach and similarly the furniture industry. This result was very insightful as the initial idea of this approach was to use MI for the consumer electronics product.

Responses to Q.6, shown in Fig. 5, were very encouraging as 76% of responses are in some degree of agreement with the notion that MI will encourage creativity and innovation towards producing a highly individualised end product. Responses to Q.7 are in line with the response to the last question which shows that the inclusion of so many actors in product design opens the door for innovation opportunities. Responses to Q.8 were mixed in agreement with the question. However, the inclination of responses is towards the positive side which provides encouragement for further research in product design for MI. Responses to Q.9, shown in Fig. 6, confirm that this product design paradigm will provide an innovative means for sustainable product design as the end product is adaptable and upgradable, as more than 50% of responses were in agreement and 27% responses were with neutral stand point.

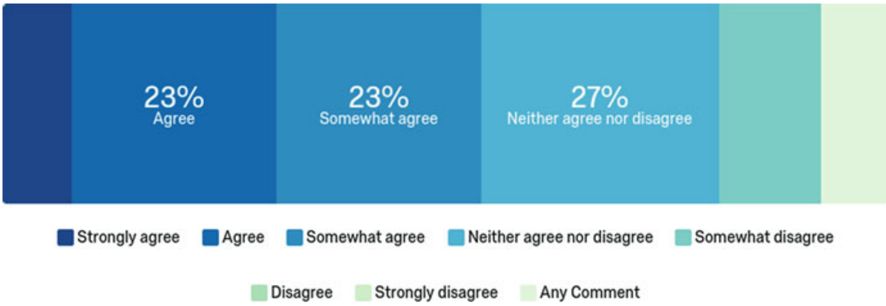


Fig. 7 Responses to Q.14, 'Networking different actors at . . . '

It can be seen in the Q.10 responses that 32% of the responses agree that the end users/customers will be able to contribute towards product innovation, as they can select and develop product modules. But at the same time, 28% responses are in slightly agree mode, which could be associated with the notion that end users might not have that skill set and knowledge of accessing requirements and converting them into the appropriate modules.

Q.11 to Q.14 present the responses to some strategical changes that will take place because of this new product design paradigm. Q.11 illustrates the mixed response to the question that MI will induct innovation in organisations in the form of organizational structure. This could be influenced by the absence of MI in current organisational structures. Responses to Q.12 indicate that MI encourages positive competition in module manufacturing companies with a few responses in disagreement. A possible explanation is that this approach is not yet implemented in the market. The majority of responses to Q.13 show that access to resources by cross networking between different actors is very important for product innovation. Responses to Q.14, shown in Fig. 7, show that more than 60% agreed that networking between different actors at the same level and guidance by the platform manufacturers provide the best of the innovative technology available.

Q.15 was a text answer question to explore practical suggestions on concept benefits of the MI over the traditional product design and customisation approaches. Responses to this question indicate that MI will provide more flexibility, distinctness, speed, serving to a new customer segment, organisational capabilities and innovation in terms of the product offering. This response was insightful as it provides many positive improvements from MI in product design. Responses to Q.16 listed some of the barriers to achieving the full innovation potential of this paradigm: complexity, dependence, differentiation, etc. Responses to Q.17 show that more than 65% of participants agree that MI will create new jobs and more accessible products. Responses to Q.18 address the issue of intellectual property rights (IPR). These present the different point of views to handle IPR, i.e., difficult to forecast, depends on who owns what, etc. It shows that this is an important issue which needs careful attention. Q.19 was a general feedback question to know the other practical impediments overlooked by the survey, as participants were industrial practitioners with experience in various product design approaches. It provides many useful insights, as mentioned in the Appendix I. One of the key issues pointed out by participants was the adoption of this paradigm by senior management leadership. This could be influenced by the lack of past study and evidence which proves the significance of this approach in industries. This was a very important feedback as the absence of past application might cause hesitation in acceptance of this approach. So further research needs to be carried out. Responses to the last question give an idea about the potential consumer segment which should be targeted for initial application of this new and innovative product design paradigm.

In summary, responses to the survey questionnaire provide multidimensional insights on the approach. It shows that product design for MI encourages creativity and innovation towards the highly individualised product, for a significant proportion of respondents. However, some of the responses were not in agreement with this new approach. This inspires to investigate this field further.

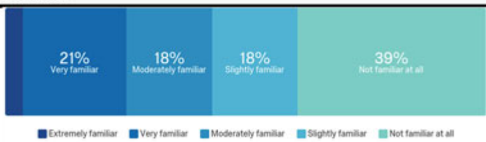
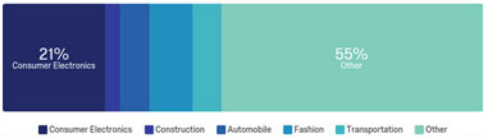
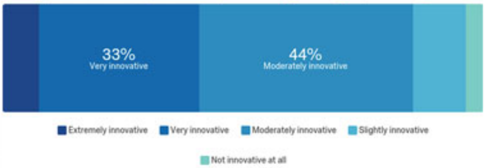
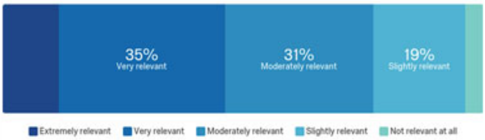
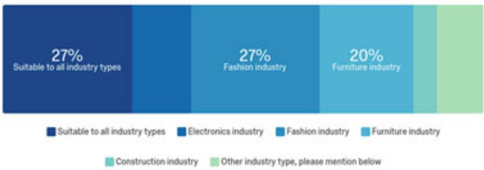
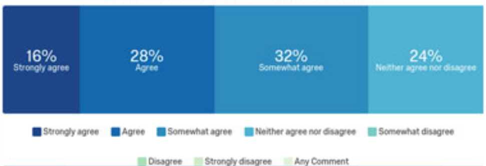
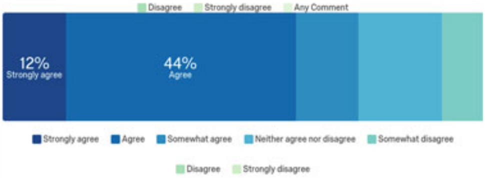
5 Conclusion and Outlook

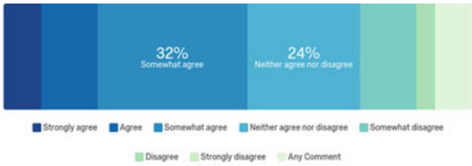
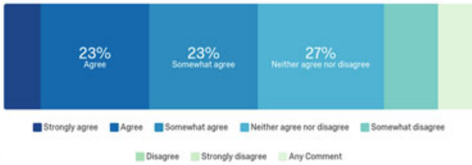
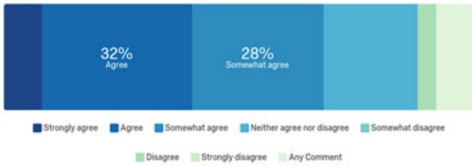
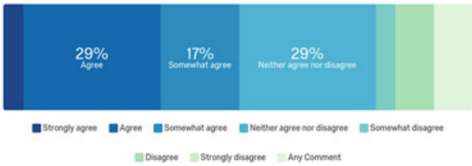
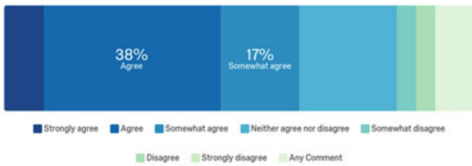
The objective of this paper is to explore the question how does a change in traditional product design approach help to nurture and accelerate innovation. It explores product design for MI, which is a relatively new product design approach, for the most individualised and technologically advanced products to satisfy the exact needs of customers, in a combined qualitative and quantitative study. Based on the identification of key areas for the realization of MI as an industrial practice, with an explorative study, a survey has been designed to get the industrial insights. Most, more than 65%, of the responses indicate that the end product from product design for MI will be more creative and innovative. This kind of innovation will lead to the most innovative and technologically advanced product.

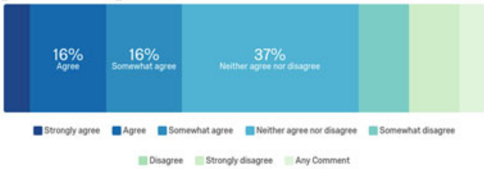
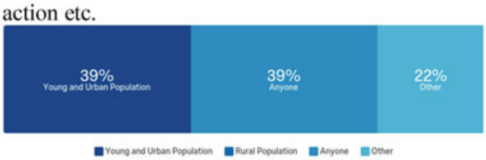
However, some responses question the feasibility of the innovation management which needs to be addressed in the future work. This kind of product design approach provides ample opportunities in the terms of product innovation and upgradable, adaptable and sustainable products, which need to be studied further.

Acknowledgement The authors are grateful to all the participants for their time and response to the survey questionnaire. We highly appreciate the feedback on text questions which helped to gain many practical insights.

A.1 Appendix I: Questionnaire Survey with Responses

Q. No.	Survey Questions	Survey Response
	Product Design for Mass Individualisation	
1	Are you familiar with the concept of product design for MI (Mass Individualisation)?	
2	What kind of industry are you affiliated with?	
3	Which statement best describes how innovative could be the new product design paradigm (MI) for product design?	
4	Which statement best describes how relevant the idea of product design for MI is for your industry?	
5	What do you think about the suitability of this product design concept to a particular type of industry?	
6	Product design for MI encourages creativity and innovation. Do you agree with this statement?	
7	The inclusion of so many actors in product design opens the door for the innovation opportunities. How do you agree with this statement?	

8	Different participant companies with different expertise will be able to provide their best in field modules for users which will make the product most advanced and innovative? How would you agree with this statement?	
9	This product design paradigm also provides an innovative means for sustainable product design as the end product is adaptable and upgradable. Do you agree with this statement?	
10	End users can develop a product module for their products and can contribute towards product innovation. How would you agree with this statement?	
	Strategical and Technological Consideration	
11	Product design for MI changes the industrial structure from vertical (different actor in a single organisation) to horizontal (different actors in different organisations). How do you think it affects the innovation in organisations?	
12	This new product design paradigm helps to encourage a positive competition between companies by giving them equal opportunities to invent and produce modules. Do you agree with this statement?	
13	Access to resources by cross networking between different actors is one of the key advantages of this product design paradigm. How important you think this would be for product innovation?	
14	Networking between different actors at the same level and guidance by the platform manufacturers provides the best of the innovative technology available. Do you agree with this statement?	

	Practical Suggestions	
15	What would be the concept improvements over current industrial product design approaches?	Flexibility, Agility to deploy new modules and improvements for products with the possibility to serve new customer segments. Speed could be an improvements, Organisational capabilities and innovation process (lean, stage/gate, agile, open innovation, etc.), Distinctness.
16	What would be the barriers to achieving the full innovation potential of this paradigm?	Complexity, Platform, IP, People, Capabilities, Dependence, Competitors, Differentiation, Approach to dependence etc.
17	This product design paradigm would not only provide innovate the product design process, but also influence the society and economy in a positive way by providing more jobs and more accessible products. Do you agree with this statement?	
18	How do you think firms should manage ownership of intellectual property rights when this many actors (other firms) are involved?	Depends on who owns what, Difficult to forecast, Seems context specific, Hard to generalise, Complex, Capabilities etc.
19	Can you identify any other practical impediments overlooked by this survey for this new approach?	Organisational Culture, Senior management leadership in adopting this paradigm, Difference between firms and startup, Product dependent, Revenue maximisation, Complexity, Who manage the transaction etc.
20	Which consumer segment should be targeted by this new approach?	

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An Exploratory Study of User Interaction with Smart Products for Customization in the Usage Stage

Ning Wang, Frank T. Piller, and Kanliang Wang

Abstract In this paper, we propose a new concept to provide customized and user-specific products, utilizing the opportunities of so-called smart products: product customization in the usage stage (PCUS) with smart products (SPs). Contrary to the existing concept of utilizing online toolkits to customize products during the time of sale, a new class of smart products (made possible by recent digital technologies and the Internet of Things) allows product adaptation and change according to each individual's needs in specific usage contexts through a new form of user-product interaction. This advanced ICT-enabled phenomenon offers many research opportunities. One of these fields is the perceptions of users of the SP's smartness, i.e., a potentially autonomous personalization of the product based on past usage behavior of a user. While such an autonomous adaptation is convenient and reduces complexity for users, users may perceive a loss of control. This paper explores the design parameters for companies to develop user interaction with SPs for PCUS. We propose that users and smart products should coadapt to better satisfy customization needs.

Keywords Smart products (SPs) · Product customization in the usage stage (PCUS) · Perceived autonomy · Perceived control · Design parameters · User interaction

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1 Introduction

Mass customization (MC) has been established as an important driver of consumer value by meeting heterogeneous preference and individual needs in customized products [16–19]. Customers specify and combine their preferred product options among a given solution space via computer-based interfaces, which are so-called toolkits for customer co-design (also configurator, choice board [14, 30, 38, 49, 52]). Toolkits usually have many features that support a trial-and-error learning process [19, 50]. After collecting the final design created by consumers when buying the product, the company produces and delivers the final product with the customized design for each consumer. We call this conventional customization approach *product customization at the point of sale (PCPS).*

However, the notable shortcoming of PCPS is that consumers have to make a decision about the final designs before they are manufactured. Due to the problem of low preference insight [16], consumers often have difficulties in evaluating whether an offering truly fits their preferences at the time of purchase. Moreover, the product usage context is diverse and changing, and it is impossible to predict every usage situation in PCPS. Simonson (2005) argues that customers often have no insight into their true preference or may even have no preference at all, so they "construct" preferences when they have to make decisions [47]. However, this spontaneous construction might be unstable or deviate from the true preference function. In such a case, the self-designed product would then not really generate value for them and might potentially lead to post-purchase dissatisfaction.

In the era of the Internet of Things (IoT), various smart products enabled by advancements in ICT (e.g., integrated sensors, microprocessors, big data technologies, machine learning, etc.) such as smart wearables, smart cookers, and smart thermostats have entered daily life. The rise of smart products leads to a new thinking for MC and offers great opportunities for new forms of customization and data-driven service personalization.

In this paper, we propose a new concept for consumers to achieve customized and user-specific products in the smart product age that is *product customization in the usage stage (PCUS) with smart products (SPs).* Contrary to the existing concept of utilizing online toolkits to customize products during the point of sale, a new class of smart products (enabled by recent digital technologies and Internet of Things) allows consumers to change them and create what they like via embedded toolkits in the usage stage. This advanced ICT-enabled phenomenon indicates many research opportunities, especially in the area of user and smart product interaction design for individualized usage. Therefore, apart from proposing the novel approach to customization, this study also aims to explore the design parameters for companies to develop user interaction with SPs for PCUS.

The paper is structured as follows. First, we elaborate on the new concept for customization – PCUS. Then we try to describe how smart products can be used for customization in the usage stage. This is followed by a discussion about user perception of control and autonomy from smart products, autonomous customization and theory of user system adaptivity, and user adaptability from user interface design. There is then a summary of design principles for user and smart product interaction to satisfy individual needs based on expert interviews and literature studies. In the final part, we discuss possible implications and future directions.

2 Product Customization in the Usage Stage (PCUS)

Contrary to the PCPS, we propose a new concept for customization named *product customization in the usage stage (PCUS).* It supports consumers to customize products to adapt to their changing needs and situations after they start to use them. The original idea for PCUS is to move product development into consumer domain [38]. For a successful implementation of this idea, the product has to be designed with the possibility to adjust and adapt to the preferences of a specific customer or context [25, 38]. So, consumers can, for instance, modify the parameters of the product attributes to fit with their changing needs, situation, and individualized usage. PCUS allows consumer learning and preferences to be detected by an immediate and easy-to-evaluate "trial-and-error" process in reality. Although PCPS allows for "complete cycles of trial and error" [50], consumers can manipulate the design over and over again virtually and, most importantly, only once the design is produced is it defined. According to connectionism learning theory, learning is an incremental process of creating and changing associations between different cues in a person's mind as a result of experiences [13, 46]. In PCUS, preference insight in a special context can be enhanced by creating a clear association between an action and result through real experience. Consumer learning can be supported by experimentation and immediate feedback. Thus, the perceived risk of making a wrong decision is reduced, and hesitation is taken away by being able to adapt the product more than once and improve it during usage.

Contrary to the PCPS, PCUS supports consumers and allows them to customize products to adapt to their changing needs and situations after they start to use them. The original idea of PCUS is to move product development into the consumer domain [38]. Manufacturers cannot predict any service that every user may need in the future because of the limitations of the closed-design mode where a designer is responsible for product design for users to use and users are passive recipients. In fact, each user's needs are highly individual.

3 Smart Products for Customization in the Usage Stage

With the advent of the smart product age, PCUS is becoming reality. SPs are a core concept discussed today in the context of the Internet of Things [29]. SPs contain ICT in the form of, e.g., microchips, software, and sensors and are therefore able to collect, process, and produce information [42]. SPs possess different degrees of smartness (capabilities) in terms of, e.g., autonomy, adaptability, multi-functionality, or ability to cooperate [42].

A new class of SPs is equipped with the so-called embedded configuration capability, which means that some of the product features are adjustable and adaptive to the preference of a specific user or context [38]. We see three different types of SP scenarios for PCUS based on the existing products in the market:

1. Smart adaptable products: Some SPs provide the configuration toolkits (either embedded toolkits or connected Apps installed in smart devices) to facilitate user customization in use. For example, the Philips Hue smart light product allows customers to create different color effect and brightness for different situations like reading, romantic moments, lively parties, etc. All the light customization can be completed by consumers in a special toolkit called "Hue system" installed on a mobile phone.
2. Smart autonomous products: Some SPs are sustained by smartness, such as adaptability and autonomy, and can automatically adapt to the situation and reconfigure themselves accordingly without any dedicated user action. This is the case with the Nest thermostat. It is able to adjust temperatures autonomously to the preferred temperature based on learning about the home dweller's living habits and the conditions it senses. In this way, product smartness is utilized to save the entire effort of manual configuration. However, consumers perceive loss of control and risk from high levels of product autonomy [42]. Often, SPs with high product autonomy lead to perceived complexity since they work silently and automatically like a black box and are difficult for users to understand [42]. Furthermore, the self-creative value from self-customization may be lost by automatic adaptation through a SP [18].
3. Smart adaptive and adaptable products: Some SPs try to balance the benefits and disadvantages of autonomous automatic adaptation. Take the case of Nike HyperAdapt. These shoes can automatically lace themselves when the consumer puts them on, but it also allows consumers to adjust the lacing by the connected App in mobile devices according to their feeling of comfort.

Beyond that, PCUS with SPs, in comparison with traditional PCPS, broadens the scope of customization beyond fit, function, and aesthetic customization to product-related service customization. For example, enabled by sensors gathering and monitoring usage data, some SPs can report on themselves and their environment in real time and can tell how the consumers are using them. Many smart sport devices nowadays like smart balls or wearables are able to proactively provide individual real-time data and personalized diagnoses and performance analysis.

4 Theoretical Background for User and Smart Product Interaction Design

From the above, we can see that not all smart products offering customization possibilities can lead to customer satisfaction. For instance, smart autonomous products enabled with product smartness and capabilities can provide highly individualized products/services (i.e., product adaptations, individual interaction, and experiences) by themselves. But not all are wanted. On one hand, smart autonomous products can save time and effort for users [3], but on the other hand, they can increase users' 'perceived disempowerment, thus impact intention to adopt' [48]. The design of user and product interaction can take an important part in influencing adoption of smart products. Therefore, the question lies in how to design smart products and user interaction in a way that satisfies the customization needs better?

Earlier research in this domain mainly relied on the concept of embedded toolkits for customization [38], but did not deploy most functions and the abilities of SP (like autonomy, adaptability, etc.). So, in this part, we try to connect mass customization, smart products, and toolkits together. Our aim is to systematically explore which kind of smart products can be utilized for PCUS and how smart products can lead to higher customer satisfaction by customization. Specifically, we are focusing on the design parameters of user interaction with smart products.

To explore this question, we rely on the following theoretical underpinnings for the proposed design principles of user and smart product interaction.

4.1 Product Autonomy

Product autonomy refers to the principle that a product does not need human intervention but instead takes over on its own [42]. Enabled by the capability of adaptive autonomy, some products can show proactive and self-starting behavior, perform physical tasks, and take over (some of) the user's normal decision-making tasks. According to Baber (2001) with the example of a washing machine, a product can be autonomous on four levels: the manual level, bounded autonomy, supervised autonomy, and symbiosis [3]. The highest level, symbiosis, assumes ongoing communication between the user and the product to fulfill some common goal. With the example of the smart washing machine, after all the laundry is put in, the user would close the door, and the machine would set the appropriate program and run it automatically. With the application of advanced sensors and ICT, many smart products are trying hard to reach the highest level of symbiosis where the users don't need to intervene at all and SPs sense the context, proactively make a decision, execute the tasks, and provide individualized solutions by themselves in the usage process.

In the following section, we discuss the problems related to user perception coming from autonomous customization enabled by high levels of product adaptive autonomy.

4.2 User Perceptions from Autonomous Customization by SPs

Perceived Autonomy

Individual autonomy is identified in self-determination theory as one of three innate psychological needs promoting intrinsic motivation for activities which lead to enhanced outcomes. It pertains to the degree to which individuals can feel the freedom, independence, and discretion to decide what should be done in a particular situation. In line with self-determination theory [44], when the task offers limited autonomy, the feeling of self-determination will be undermined, which results in diminished self-motivation and dissatisfaction of outcomes [34]. On the other hand, when individuals perceive autonomy, self-initiating and regulating work will lead to empowerment, and mental health (e.g., satisfaction) will be enhanced. Feelings of autonomy help individuals to identify with outcomes and perform tasks out of enjoyment and satisfaction. Previous research has shown that the intrinsic motivation through higher perception of autonomy is likely to be sustained over time and enables individuals to continue acting [34].

With regard to autonomous customization by SPs, users are likely to perceive lack of autonomy because SPs change and adapt to users and contexts automatically without any user dedication. Also, users cannot identify them as the independent and causal agents on the results, which is completely dependent on the SPs. This may lead to dissatisfaction with the performance of SPs that are responsible for the results. Although autonomous adaptations by SPs can save time and effort for the user to perform tasks, it also takes over the work done by users before, such as the freedom to make decisions about product adaptation. Hence the subjective perception of autonomy, in terms of freedom to act on their own to reach their personal needs, cannot be fulfilled by SPs with autonomous customization. Furthermore, the intrinsic motivation to perform out of enjoyment and satisfaction cannot be achieved.

On the contrary, some SPs allow user participation when producing and delivering preferred configurations or product solutions in the usage stage. For example, users are involved in developing their favorite solutions or making some decisions themselves. This kind of participatory behavior in satisfying the specific usage needs can be one of the main drivers of customer satisfaction with the performance and value perception [2, 9]. Continuous perception of self-determination through high user autonomy would be easily achieved and enable users to continue performing the product customization in use out of interest and enjoyment. This would enhance user satisfaction with the outcome, since users would recognize themselves as the cause of the outcome. In addition, according to a study about perceived autonomy from app developers, a platform developer will produce apps of higher quality and tend to continue to develop if they are empowered with a perception of high autonomy [26]. User engagement integrated with high-level product autonomy could be helpful for continuous co-design or creation with SPs over time. Based on the above, an optimal level of product autonomy with the option for users to customize for themselves would be better for perceived autonomy.

Perceived Control

Except for perceived autonomy, perceived control is also related to SPs for PCUS. Perceived control is seen as essential for individuals' general wellbeing and is often defined as the need to demonstrate competence and mastery over the environment [54]. It represents the extent to which individuals perceive that they are able to exert control over the environment and influence the process and outcome and is responsible for the outcome of a given situation [11, 15]. If the SPs do the autonomous adaptation and users are not responsible for the adaptation result at all, users would tend to perceive loss of control.

In fact, the feeling of control is connected to an emotional response of dominance in environmental psychology. As indicated by Mehrabian and Russell (1974), a person's level of control is reflected by dominance, influence, and autonomy [32]. Some previous research states that the concept of control is rooted in the need for competence in influencing the environment and for autonomy of behavior [7, 15, 54].

Perceived control has also been widely investigated in research about the interaction between users and web-based environments or various information systems [33]. It measures the user's experience of level of control, frustration, and confusion during interaction with the system [10]. In web-based environments, the feeling of control can be present through manipulation achieved by virtual control, which allows consumers to exert their control over products directly by manipulating images and operating various functions [22]. When users are interacting with SPs, they directly manipulate the product, which contributes greatly to product understanding. In PCUS, product information and feedback are presented through multiple sensory cues and channels. Any adaptation changes made by users, e.g., changing the parameters, adding a new service or function, turning on or off the automation, etc., can be seen, and the outcome of the product can be easily evaluated in reality. Product customization by users (e.g., users specify the product changes at a certain moment) through connected toolkits in PCUS would be able to affirm their competence and impart a feeling that they are able to influence the product. In autonomous customization by SP autonomy, the SP completes every change for users, which does not give users the opportunity to demonstrate their competence and ability to influence. Furthermore, if the product works autonomously and makes the ongoing changes dynamically, users can get confused, face perceived complexity, and will probably reject the result since they are not aware of when and how the product works [42]. If users try to influence when they are not satisfied with automatic adaptation but do not have the supporting tools, they are likely to get frustrated. Therefore, in autonomous customization, users are not enabled to evaluate and determine but surrender and become a passive recipient.

As is found in previous research, having a sense of control has a positive influence on the performance of a task [4, 5]. The higher degree of control the users perceive, the more they are likely to exert cognitive effort, show interest while problem solving, and continue taking actions even in the face of difficulties and failures.

Furthermore, previous studies have found that, when users are granted the freedom to self-select, self-service, or get involved in the design practices based on technology such as tools, for example, by specifying their own settings on how an application should behave, they perceive a sense of control in their experience with the technology [6, 12]. To enable users to configure the product components or product-related services is a complex but applicable approach to grant user control. If users can configure the SPs and related services through embedded toolkits, they can gain a greater perception of control, which promotes the user's development and design activities, further enhancing consumer enjoyment and satisfaction with the outcome.

Moreover, Furby (1978) argues that the more a person is able to exercise control over an object, the more they will experience this object as part of the self and evolve a sense of ownership [20]. If users cannot attribute the outcome to themselves at all, the feeling of accomplishment and subjective contribution to the self-design process will be missing [17]. This proud feeling of accomplishment serves the need for feelings of competence and efficacy deeply embedded in human nature [21, 55].

We can assume that autonomous customization by SPs diminishes users' perceived control and would thus lead to a negative influence on satisfaction with the process and outcomes from SPs. The feeling of control can be achieved during the design of a system or the way users are integrated. However, if the user tries to extend or specify everything, they might be overwhelmed by the complex configuration process. So, there is a trade-off between smart product autonomy and user control complexity.

4.3 User Adaptability and System Adaptivity

In the area of adaptive user interface design, Bunt [8] says there are three different potential solutions to manage the complexity problem of interfaces: (1) an adaptable interface that allows users to customize the application to suit their needs, (2) an adaptive interface that performs the adaptation for the users, or (3) a combination of adaptive and adaptable solutions, which is an approach that would be suitable in situations where users are not customizing effectively on their own.

System adaptivity is defined as the ability of a system to adapt automatically to different users according to the context with respect to functionality, content presentation, content selection, and user interaction [23, 37, 45]. This system predicts the optimal product configuration or service and automatically adapts based on comparison of the customer's profile to certain reference characteristics [1, 43]. User adaptability places users in control of customizing or tailoring the system according to their individual needs and situational requirements [8, 31].

As we can see from the definitions, these two approaches keep the system adaptable and changeable during usage. However, the adaptive approach can suffer from some users feeling a lack of control over the process, a lack of transparency, and a lack of predictability [8, 37]. In addition, human preference is heterogeneous, and the situation changes over time so that it is impossible to anticipate the requirements of all users and always provide the best configurations. Therefore, it is necessary to allow a coexistence of automatic system adaptivity and user-controlled adaptability resulting in a flexible system through shared initiatives [37, 45]. An example of the combination of these is the auto-correct function. Users are able to switch off this function when auto-correct does things to the text that the user does not want. Fischer proposed shared decision-making between purely adaptive and purely adaptable systems, in which users and system components contribute to the modification of a system [45].

Actually, this applies to PCUS with SPs as well. System adaptivity is quite similar to autonomous customization by SPs, in which SPs supported by sensors and advanced data analysis that can detect the surroundings personalize content, change the product function or form, or come up with great suggestions for the service in different contexts. However, it is difficult to anticipate every usage situation. For personalization without users by SPs, the actions done by algorithms may not exactly fit with user preference, which requires a thorough understanding of the users' context and habits. This becomes especially difficult when situations are constantly changing. In the end, it is the user who knows best. Moreover, automatic personalization might not always be sufficient. End users might want not only to reconfigure the product, but they might also want to add new a behavior such as a new service or applications specific to their needs.

We propose that there should be a coadaptation between user and smart product, which means a trade-off between SP automatic personalization and user-controlled customization. By means of coadaptation, this can enhance user productivity, optimize workloads, and increase user satisfaction with increased control and autonomy.

An illustration for the coexistence of SP adaptivity and user adaptability is the Nike smart shoe. It provides consumers with the option to customize after they have bought it in a way that the shoe itself can do itself automatically and personalized tying. The consumer can also adapt the tying according to their preferences via the connected toolkits.

5 Design Principles for User and Smart Product Interaction Design for PCUS

Complementing the theoretical discussion in the last section, we conducted a number of semi-structured interviews to derive additional insights into the research topic. Our objective was to learn from designers and product developers commissioned with developing smart products about how smart products enable our idea of PCUS. We were especially interested in the design parameters companies follow when developing the user interaction with SPs. We conducted five expert interviews with experienced smart product designers (Table 1), which helped us to suggest

Table 1 Semi-structured expert interviews

Interview no.	Company	Area
1	Ambihome, product designer	Smart home
2	Philips Hue, product designer	Smart light
3	Physiosense, product designer	Smart chair
4	Vestel, product designer	Smart TV
5	University of Southern California, professor	Product development engineering

three preliminary design principles to develop SPs for PCUS. These principles are proposed to elevate the feeling of autonomy and control through certain user and smart product interaction designs.

5.1 Cooperative Adaptation: Shared Control Between Users and Smart Products

5.1.1 User and SP Coadaptation: Cooperation Between Users and SPs to Better Fulfill Customization Needs

According to theory of system adaptivity, a system can perform tasks for all stages from observing communication, deciding whether to adapt, generating and evaluating different variants, to finally selecting and executing one of these options [36]. User adaptability and system adaptivity should compensate for each other due to the shortcomings of each approach [28].

SPs that customize products to specific user needs should be under user control. Smart, connected products can be controlled through toolkits embedded within them or that resides in the cloud. Users have an unprecedented ability to tailor product functions and personalize interactions as they wish [39]. It is also confirmed in the interviews that it is important for users have the option to reconfigure automatic adaptation by SPs (Interview 3,5). Users should always have easy access to self-controlled customization (Interview 1,2).

In the early usage stage, users should be more active in specifying their preferences, and SPs need to be talkative to gather more usage data and lead users to express their preferences themselves (Interview 3). At this stage, default starting solutions can be provided to reduce user effort in specifying the product at the beginning. Self-customization could be dominant at this stage. In the mature usage stage, SPs could play a more active role. Based on the learning of user habits or preferences and continuous improvement, the SPs could provide adaptive solutions to users. Therefore, users don't need to expend effort on always controlling the product but still adapt the product in accordance with their preferences (Interview 2).

Even during the mature usage stage, the user's involvement is important to fulfill needs in specific situations. When the SPs recognize missing values or capabilities to perform the task automatically, the users should be informed to take action.

5.1.2 SPs Perform Routine Tasks to Reduce Effort for Users and Prepare Support and Suggestions for Users, but Users Are Empowered to Make Decisions [39]

The experiment by Opperman et al. in evaluating adaptable and adaptive software systems showed that users prefer to deal with systems based on shared decision-making: the user can act on their own and get support from the system whenever they like. Based on this, the adaptive SPs should do more of an assisting job than an executing one. That means SPs are responsible for preparing support and suggestions for the users, but users have the freedom to accept or reject the suggestions [37]. Whenever possible, more than one adaptation suggestion should be offered, as SPs are usually not able to identify the users' needs precisely. The user should have the freedom to select from a number of different adaptations suggested by the system.

The automation capability of SPs should be utilized to enhance the work of users, making users more capable and effective [39]. As discussed in robotics design, automation should be used to augment human abilities by taking the dirty, dull, and dangerous tasks and assisting users to finish exciting, creative works [35]. For example, user-controlled SP adaptation should allow the user to take the initiative and issue the demand. Specifically speaking, SPs should take care of the routine tasks (proposal and execution) and entrust the creative tasks (initiative and decision) to the user.

When we design tools for PCUS, we should think of users and SPs as collaborators, not as replacements. To realize this, there should be shared control and collaborative work on the product adaptation between SPs and users. SPs can provide users with personalized solutions, suggestions, and feedback, and users can decide what the smart products should do and select their own content via embedded toolkits. However, suggestions or feedback from the SPs should not disturb the user unnecessarily in their work. SP automatic adaptation features are only aids to the user, and suggestions should not take the user's attention away from the real task.

5.1.3 Provide Possibilities for Users to Override or Change an Autonomic Adaptation from SPs

The feeling of user empowerment derives from flexibility in defining their own choice [53]. Therefore, users should have the possibility to control the autonomous choice set composition via self-choice. This means that users have the ability to reconfigure and adjust actions from SPs.

In addition, the user should always have complete control over product smartness. There should be an option to stop the work of the SP or interrupt actions of SPs at any time, so that users feel they are in control of the product. For example, users are provided with a switch to turn the automation function on or off. If the SPs are doing something that users don't want them to do, users can disconnect the service, and SPs lose control over the outcome [56, 40].

5.2 Empower Users with Control by Product-to-User Communication About the Product Progress

Unlike with PCPS, users have to translate their needs into virtual product design. In PCUS with SPs, the interaction of the product and user can be both direct and mutual. It is more like a "communication." In PCUS not only do users directly communicate with SPs by transferring their preferences into the product and controlling the product via embedded toolkits (user to product interaction), but also SPs can present information to users in different ways (product-to-user interaction) [36]. This makes SPs dramatically different from traditional products. To create high-quality product-to-user interaction, embedded toolkits play an important role. The toolkits are the intermediary medium for users to collaborate with SPs based on the output from SPs and should be designed to reduce user customization effort, empower users with control by improving product transparency, and convey individualized feedback to users.

5.2.1 Present Sufficient Indicators and Feedback About the Product Progress, so that Users Can Feel in Control of Smart Product Actions

A good design provides users with a conceptual model for what is happening, with feedback and visibility that promotes product understanding and a feeling of control. Except for enabling users to self-select content, which is realized in the user customization we proposed before, delivering feedback to users is also identified as one main source of user empowerment [51]. For autonomous smart products that operate automatically without direct input from the user, some actions may be unwanted or illogical from the user's perspective, so it is important to inform users about why the product performs these actions. By equipping users with feedback on what the product is performing at a certain moment, the visibility of the SP's actions will be increased [40, 56], and the perceived complexity from not understanding the product functions will be reduced [41].

5.2.2 Increase the Process Transparency of How the Different Product/Service Adaptation Is Generated

The transparency of the service process in smart service products is proposed to positively influence users' attitudinal and behavioral responses to these services [56]. Users want to know not only what actions the product has taken but also why and how an outcome is generated. This kind of transparency is also proven to be able to improve users' perception of control [56].

Especially when generating individualized services, different sources of usage data are collected and integrated by the SPs autonomously. Users can easily feel loss of control not only in the function of the product but also in the data usage. This perception of control over the process will improve if the transparency of data usage is available to users when they want to know. One example of the transparency would be that users are able to be informed about what kind of data is collected and how the data is transmitted and integrated. Users therefore not only see the aggregated data or personalized suggestion but also feel in control of how the solution is generated. The transparency of the process can be reflected in the form of the protocol or working documentation stored as a feature in the service system [56].

5.3 Trial-and-Error Learning by Both SPs and Users

In the smart product age, the trial-and-error learning process applies not only to users but also to SPs. One of the big advantages of SPs is the ability to learn actively from users about their needs by collecting, integrating, and analyzing daily usage data. Trial-and-error learning processes are experienced by both users and SPs. Since the product functions are changing dynamically to fit with different environments and users, users have to learn not only about their preferences but also about the SP's actions and processes via interaction with toolkits as mentioned in principle 2. In addition, a lot of in time usage data is generated. Users have to learn to interpret the data and understand the meaning behind it.

5.3.1 SPs Learn to Continuously Adapt to Users and Provide Exciting Features for Users

Adaptability is an essential capability for smart products to continuously offer customized products/services to users. Enabled by adaptability, SPs can improve themselves by learning from the user's profile, usage pattern and habits, and so on. For example, if the SP has noticed that the users don't like a certain kind of activity at all, the smart product will not make proposals about what the users don't like any longer. With the advanced intelligence embedded into SPs, the age of symbiosis is arriving. Smart products are working together with users to achieve the same goal. With learning and the error process, SPs stay flexible in gathering and processing information, making decisions and thus providing individualized solutions dynamically.

Moreover, SPs can be used by a manufacturer as a means to collect usage data on users' everyday activities. Utilizing this daily usage data, SPs can continuously provide exciting features to users to satisfy the unmet but not noticed needs of specific users (Interview 5; Lu 2016). As is stated in Kano model, exciting features are those that are unseen by users but, when implemented, will yield increased user satisfaction [27]. This distinguishes PCUS in the smart product age from traditional mass customization where it is impossible to get information about usage behavior and only performance features can be provided (Interview 5, Lu 2016) [24].

5.3.2 User Learning About the Meaning and the Value of the Data

The special problems coming from PCUS with SPs are information overload due to the large amount of behavioral data and understanding the information. If the data are not presented to users in an appropriate way, confusion and loss of control would likely result and thus decrease the value SPs create.

To facilitate user learning about usage data, it is necessary to provide users with high-quality data interpretation. This must be easy to understand, insightful, user-friendly, and presented with the aim of helping users truly understand the meaning of the data and how to improve [49, 51].

5.3.3 Smart Products as Tools to Facilitate the Trial-and-Error Learning Process of User Co-creation in the Usage Stage

SPs are not finished products that are just for users to consume but rather unfinished and open products allowing users to become both consumers and producers. Based on the embedded toolkits or interfaces that are part of SPs, users are enabled to create the extension of the SPs according to their needs and experiences. Take the example of the Philips Hue, which provides modules for users to develop their own apps connected to the product system or program to add new functions. These modules consist of end user-friendly navigations, programming language, and programming examples as starting points to help users to explore their co-design activities (Interview2; [37]). In addition, the user community can be included in the toolkits to learn and exchange knowledge and experience with others, so that users can be empowered to resolve their own problem. Users feel empowered. Through the learning and trial creation process supported by smart products, users not only achieve the preferred products and services but also achieve creative value [16].

6 Conclusions

This paper discusses users' perceptions of control and autonomy in situations of autonomous customization with a smart, i.e., adaptable, product (SP) in the usage stage. To enhance users' positive perceptions and reach higher consumer satisfaction, our research strives to understand how smart product can realize the idea of PCUS and which design parameters in the interaction process between users and SPs support this process. Based on theoretical foundations and semi-structured expert interviews, three preliminary principles to develop SPs for PCUS are proposed. Especially, we propose the concept of user and smart product coadaptation, which means that user participation is included to complement autonomous customization by SPs.

This research connects the fields of mass customization, toolkits for user co-design, and smart products enabled by the IoT by proposing a new customization concept to be realized in the smart product age. PCUS with SPs extends our traditional understanding of customization into a new horizon. This research provides a different perspective for companies to transfer NPD especially to the users. It also explores how smart products can be used for customization in the usage phase and how smart products can lead to higher customer satisfaction through the design of user and smart product interaction. Specifically, it could be insightful for companies to design SPs for offering better customization or service-driven personalization.

PCUS with SPs provides a new opportunity for user co-design, where the design process is not just based on the ability of expert designers. In the conventional toolkit-based customization approaches (PCPS), novice users lack knowledge about product characteristics and hence are dependent on what the provider has suggested before. In the new customization approach proposed in this paper, however, they become able to experiment with real feedback during the usage stage and build consumption competence that then enables them to complete a more meaningful customization. However, the proposed principles of the design parameters for smart and user interactions still need to be tested in a larger empirical study. A special focus should be how consumers react to the shared control and collaborative adaptation in different usage contexts.

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Datamodels for PSS Development and Configuration: Existing Approaches and Future Research

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Abstract Product-service systems (hereinafter referred to as PSS) are a hybrid combination of products and services. They are problem-oriented solutions which address the individual needs of customers. To fulfill these individual needs, a customer-centric development of PSS is necessary. Therefore, a customizable product is essential, which can be designed with parametric and knowledge-based models.

One of the biggest advantages of a PSS is at the same time one of the biggest challenges: addressing current requirements of customers during the life cycle. This results in the need of modifying the product during its use. In view of the existing hardware, an arbitrary modification is in contrast to product development not possible, which calls for refinement and adaption design.

In this paper the idea of a variable product model – parametric during the development and case and rule based during the life cycle – is discussed, to show the advantages and assign different models to the phases of the life cycle.

Keywords Product-service system · Parametric model · Knowledge based · Rule based

1 Introduction

In today's world with globalized markets, it is more and more difficult for companies to distinguish themselves from competitors only by technical product characteristics. This is, among others, due to the rapid dissemination of knowledge and the international harmonization of standards.

One way of avoiding total comparability is to combine product and services to integrated problem solutions. In order to fully benefit from the advantages of the so-

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called product-service systems (PSS), an integrative relationship between product and service needs to be created [30].

According to the existing literature, the quality of a PSS is influenced by the setup of its development process, which requires service and product components be treated equally. The resulting PSS is a solution which fulfills the individual customer needs. Whether the value proposition and revenue is primarily achieved by the product or service components is only a secondary aspect [31].

The customer needs result in individual requirements that lead to customer-specific solutions, which calls for individually configured development processes. Literature agrees on that, but the identified approaches remain mainly vague and conceptual. Furthermore, the approaches are discussed on very simple or very special examples which makes the transfer to relevant use cases difficult [8].

PSS design cannot be seen as a research stream per se [2]. In case of the lack of evaluation of the existing approaches, it is impossible to use one of them as a generally accepted and standardized approach for the development of PSS [11]. The number of papers, which focuses only on design, is very limited because most publications focus primarily on their predominantly field of research and discusses the development of PSS as a secondary field of interest [2]. This paper focuses on the development of PSS and the models which are needed for this process. Topics that exceed this, such as life-cycle assessment, are not examined in this paper.

The paper is structured as follows, first a brief overview of the used research methodology is given and the solutions presented in this paper are sorted into it (Sect. 2). Afterward an overview of basic informations of PSS and existing approaches to the development and configuration of PSS is given (Sect. 3). Subsequently an approach with parametric models for the customized development of PSS is presented, and its limitations are shown in Sect. 4.3. Based on this, the need for the extension of this approach is explained and the potentials of the adaption of approaches from mass customization (MC) are shown (Sect. 4). Finally, an outlook at the next steps and future research is given (Sect. 5).

2 Methodology

The work on which this paper is based follows the design research methodology (DRM) from Blessing and Chakrabarti [4]. The DRM is a framework for research in design methodology and is divided into four main sections (stages) which are shown in Fig. 1. The first stage, the research clarification, leads to the identification of the research gap on basis of a comprehensive literature research. The descriptive study I (stage two) includes an empirical data analysis, further literature research and results in a deeper understanding of the research gap and the current situation of the research field. The results of the first two stages are presented in Sect. 3.

The findings presented in this paper in Sect. 4 are part of the third stage of the DRM (highlighted in gray in the figure). In this stage the development of methods and tools takes place with the help of prescriptive studies. For the descriptive study,

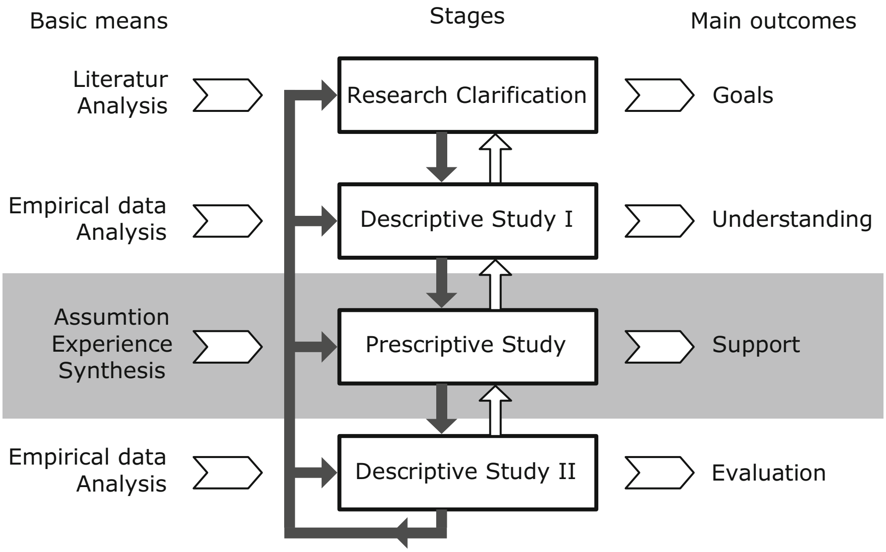

Fig. 1 DRM according to Blessing and Chakrabarti [4]

the shown research lack (based on the first two stages, Sect. 3) is compared to similar problems in other research fields (in this case the classical product development), and the possible solutions and methods were adapted and transferred to the problems of PSS development.

In the last section of this paper (Conclusion and Further Research), an outlook is given on the following evaluation of the developed methods, which in the DRM framework sorts in the last stage (the descriptive study II) [4].

3 Product-Service Systems (PSS)

Literature discusses various characterizations and approaches for development and configuration of PSS. Tukker [33] analyzed the existing literature about PSS and asserted that in the period just after the year 2000 the most common concepts of PSS were defined, for example, Mont [20], Morelli [21], and Meier [19]. In the current literature, authors repeatedly present their own characterizations of PSS, but they do not differ significantly from the already existing concepts[33].

From the authors' point of view, it can be seen that there is no generally accepted definition of PSS. Even though many researchers refer to the approach of Tukker, there are always attempts to redefine PSS. This can be partly attributed to the heterogeneous research community, which includes members from various disciplines. Furthermore, the current literature emphasizes that further research is needed to achieve an efficient PSS design methodology [35].

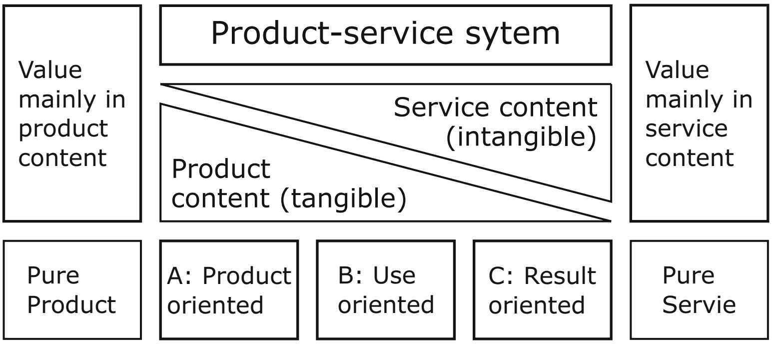

Fig. 2 Main PSS categories based on Tukker [32]

In 2004, Tukker [32] developed a characterization which is often used for PSS descriptions. He uses three main categories which are product-oriented, use-oriented, and result-oriented (shown in Fig. 2), with eight subcategories to classify different PSS.

With regard to the existing characterizations of PSS and the presented theses on design research, the following major characteristics of PSS can be named:

- coequal development of product and service components
- integration and addressing of individual customers and their need in the development process
- monitoring and addressing of the customer requirements during the whole life cycle of the PSS

These characteristics are the basis for the understanding of PSS in this paper.

3.1 PSS Development

An important point named before is the coequal and integrated development of PSS. The approaches which can be found in literature are mostly restricted to partial aspects of the development process or concentrate only on single domains of PSS development [3, 35].

Steinbach presented an idea based on the Characteristics-Properties Modeling/ Property-Driven Developments (CPM/PDD) approach of Weber [29]. Here, Weber [38] distinguishes properties, which describe the behavior of a product, and characteristics, which capture the shape of a product, defined by the structure, the arrangement of the components, as well as the parameters of shapes, dimensions, materials, and surface. Characteristics can be determined directly by the developer in contrast to properties, which can only be influenced by change of the corresponding characteristics.

These properties and characteristics are used by Steinbach [29] to characterize his PSS development process. He integrates service development and modeling and uses the properties to represent the result dimension of services (and the whole PSS).

Müller [22] presented a process-oriented approach of "layer-based PSS development" from the point of view of system engineering. The approach is adapted from the V-Model® XT and combines the different perspectives "development and management," "life cycle," and "architecture" of PSS. The basic framework is presented as a 150% process. This process must be tailored for each new PSS development task, depending on the scope and requirement of the intended result.

The idea of "blueprints" presented by Morelli [21] shows processes for the PSS development based on various already successfully planned PSS. This is similar to the strategy of using templates in product and software development.

3.2 Computer-Aided PSS Design

The approaches described so far consider PSS development from the product or systems development perspective. In the classical product development, the mechanical computer-aided design (MCAD) is already far developed. The computer-aided development of services (SCAD) has not yet the development status of MCAD. In the service development, there only exist individual approaches for computer-aided design solutions.

With the service explorer, Sakao et al. [28] introduce such a SCAD system. In the context of this approach, service is seen as something a provider does to get the recipient from a status to a new status that he desires. For this purpose, the requirements and status of the receiver are initially modeled. Afterward, transformation rules are developed, which are implemented as elementary units similar to the feature-based modeling in MCAD systems. The network of states and transformation rules adapts the structure of functionality known from physical products (e.g., Roth [26]) to service engineering.

Akasaka et al. [1] presented an approach in which they developed a service design catalog for the service explorer. The catalog is a system which provides service modules for functions to be implemented, based on a merger of service parts for a PSS. This catalog should extend the service explorer with a KBE (knowledge-based engineering) tool. According to the authors, the design catalog developed by Roth [26] as a knowledge base for design knowledge is the basis for their development. Here, it has to be mentioned that the typical setup of classification part, main part, and selection characteristics is not used.

Based on case-based reasoning, Kuntzky [15] presents an approach for a knowledge-based development system for PSS. She uses the formulation of requirements, knowledge about the composition of specific PSS and a modular design of PSS components. It is possible to configure PSS in the early development stage if the same or similar PSS and the associated requirements can be found and adapted in the case base.

Yang et al. [39] presented the idea of knowledge-based assignment of service modules which is the basis for a life-cycle-oriented approach. These modules are released based on data monitored during the product use. They describe a possible application scenario in their publication, but no information is provided on the necessary knowledge base and evaluation of events or their design. Furthermore, no details are given on reasoning mechanisms, which are typical for knowledge-based systems. Until now there is no documented connection of SCAD and MCAD in one solution.

In the context of PSS development, Klein [13] presents a KBE modeling language (KbeML) as a standardized representation for codified engineering knowledge. In his point of view, KbeML, which is based upon a formal machine-readable representation of knowledge, is an enabler for making development-related rules and algorithms accessible for different CAx systems. The advantages over existing modeling languages such as MML (MOKA modeling language, invented by Brimble et al. [7]) and the general applicability have to be shown.

3.3 Computer-Aided PSS Configuration

Besides the coequal and integrated development of PSS, the other important point is the integration and addressing of individual customer requirements, not only in the development process but also during the whole life cycle of PSS [19, 20]. To address this issue, configuration and later reconfiguration of PSS are beneficial. Therefore, in the following section, the approaches of configuration of PSS which are discussed in literature are presented.

Laurischkat [16] concentrates on the configuration of service components of PSS. According to her, a generation of PPS (which she uses equal to a configuration) can be made based on five basic criteria of PSS. The criteria of value proposition, life-cycle phase, reference and allocation, legal liability, case distinction, remote support, degree of automation, and accountability determine whether a service component has to be included or not. This is modeled by decision tables or production rules.

Bochnig et al. [5, 6] published an approach of integrated PSS development including the possibility of configuration. They introduced a CAE tool, based on 16 modules, designed to extend and link existing development tools from various disciplines (mechanics, electronics, software, and service). In the tool PSS variants are generated by combining existing PSS modules. The tool furthermore implements services by symbols in the CAD environment and displays the interdependency among different elements. Until now, no documented modification in the physical product model through different services could be found.

Aurich et al. [3, 27] identified modularization as a promising approach for the integration of product and service design. In the approach, the configurability of PSS is considered, focusing on the possible product and service structures for PSS. Both process modules for product and service design must be linked, parallelized, and integrated with appropriate inputs and outputs and the incoming and outgoing information. Aurich et al. [3] use combination matrices in his approach focusing on possible product and service architectures for PSS.

Mannweiler [18] presents an approach with predefined blocks, which are predominantly product components. It is an approach for industrial PSS based on customer requirements which the designers attempt to fulfill by aggregating these building blocks. Subsequently, the degree of fulfillment is evaluated.

3.4 Modularization

Since modularization seems to be a promising enabler for configuration (according to individual approaches), a more detailed view of the possibilities of modularization will be provided in the following.

Modular products are machines, assemblies, and components that fulfill various functions through the combination of different functional units (modules) or assemblies [23]. The modular design is degenerated as combining and implementing functions of a technical system in independent, functional modules. Standardized interfaces are a requirement for the interaction of different modules. A disadvantage of modular products is the higher production effort due to these additional interfaces [14].

As an advantage, the customer can benefit from the flexibility resulting from the exchange of modules during the life cycle. This can be the upgrading of a product through higher quality of individual modules, the simplified repair of the entire product or system by the exchange of individual modules, or the adaptation of the product to changed application and ambient conditions. In this way, modules can be further developed during the product life cycle in order to allow technical modifications to be incorporated into the product and thus to react to new technologies as well as new or changed standards or laws[14].

So far, the focus has been on the modularization of products. Modularization of immaterial offers has been discussed by Lubarski et al. [17]. They consider the modularization of service components in the field of PSS. For creating their framework, they analyzed existing modularization methods by discussing which method is localized in which phase of modularization related to the structure level. Discussed phases of modularization are information capturing, decomposition, structuring, module creation, interface definition and testing, and the structure level: logical, temporal, and combined/complex structure.

But like in the computer-aided development, until now there is no documented connection of product and service modularization in one solution.

3.5 Intermediate Result

There are many documented approaches that are neglecting the planning and design of configurability and reconfigurability from PSS over the product life cycle, even though the reconfiguration of PSS during the life cycle reflects a key advantage of PSS and is contained in the second basic characteristic of PSS.

Referring to the first presented characteristic of PSS, a combined development and therefore a combined modeling of product and service parts represented by a joint parametric data model have not been documented so far. There are, however, very few approaches for rule-based and case-based configuration (e.g., in the work of Laurischkat [16]), but due to the absence of parametric models, no model-based configuration has been presented.

The potentials resulting from the targeted modeling of a solution space in the PSS development have already been described by Gembarski et al. [8]. Such solution spaces for physical products have already been described in the area of mass customization (MC) by product configurators. Since parametric CAD systems offer a great potential for (automated) variant design, such approaches for PSS design would be highly beneficial, which will be discussed in the following (Sects. 4.1, 4.2, 4.3, and 4.4).

Besides different development and configuration approaches, the topic of modularization was discussed. In product development modularization is an enabler for variable and during the life-cycle configurable products [14, 23].

That the theory of modularization can also be applied to services has been shown by Lubarski et al. [17]. Gembarski et al. [8] have already shown that the development and configuration of PSS can benefit from MC techniques. In the field of MC, Pine also describes modularization as an important enabler.

Pine et al. [24] are also convinced that the company's own processes, administrative or directly related to the provision of services, must also be developed as a modular building block system. These are configured specifically for a customer solution as required.

The transfer of the idea of modularization to PSS is considered in more detail in Sect. 4.5.

4 PSS Modeling Principles

In addition to the classical geometric models, the development of physical products also includes parametric and feature-based models. In current CAD systems, all common modeling techniques of parametric, feature-based as well as knowledge-based design are available [9].

As these models are already established in conventional product development, the CAD and the underlying data models for physical artifacts will be used as a reference to derivate models for the PSS development. In the following the correlation and background of the CAD models are presented in the context of product development and then transferred to the field of PSS research.

4.1 Modeling Principles in Product Development

Models of products picture real or planned product characteristics in a formal way [10]. They separate what is essential for the respective task from the unessential and are thus task-specific and purpose-oriented. Product models can be perceived by several people and used for communication between the parties involved. The models serve as prerequisites for the development and design of a system [25].

Like mentioned above, parametric, feature-based, and even knowledge-based modeling is state of the art in the product development of physical components. These techniques are built on conventional CAD systems (shown in Fig. 3) and have an inner connection [34].

Parametric models have, in contrast to conventional (rigid) ones, no fixed values (length, angle, etc.) in their geometry representation; they are substituted by formulas and constraints. In feature-based systems, the models include additional informations (e.g., in terms of production characteristics) besides the geometric data. The basic elements of these systems need to be parametric to be flexible and adaptable to their environment. Due to this, feature-based systems can be understood as an extended parametric system [34]. Aspects of the design process can be automated by knowledge-based design using the ability of reasoning and drawing conclusions in the system [8].

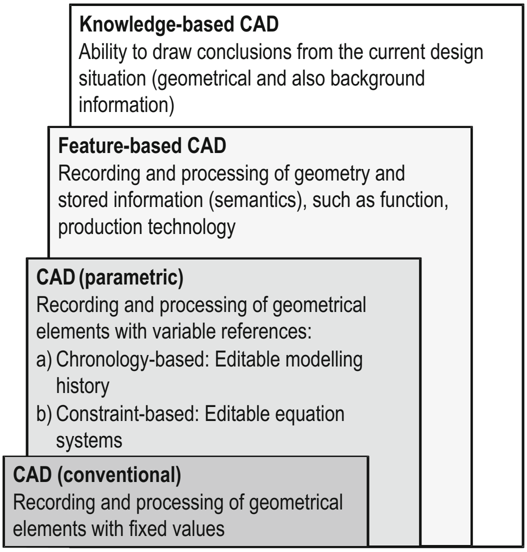

Fig. 3 3D modeling based on VDI 2209 [36]

Vanja [34] points out that incomplete models or the skipping of models leads to the situation that the techniques quickly reach their limits, and the corresponding solutions cover only a very limited scope.

This statement is very interesting, especially with regard to the awarenesses gained during the analysis of existing approaches in the PSS development and configuration. It was found in the analysis that none of the existing approaches are based on a parametric model, despite the fact that a parametric model releases the developer completely from predefined blocks and is thus a very powerful tool in product development.

4.2 Parametric Models in Product Development

In development of physical products, parameters are used to characterize the properties of a system by referring to geometry, kinematics, tensions, deformations, dynamics, or other aspects. In the common CAD product development process, numerous parameters are defined "directly" by the developer, which can be automated by the parametric modeling [34].

CAD systems reduce the number of independent parameters by establishing relationships between directly defined parameters and system elements. The defined mathematical and logical constraints represent mathematical models with parameters which usually have a hierarchical structure [34].

The parameter-based relations in a product structure of an assembly design are shown in Fig. 4.

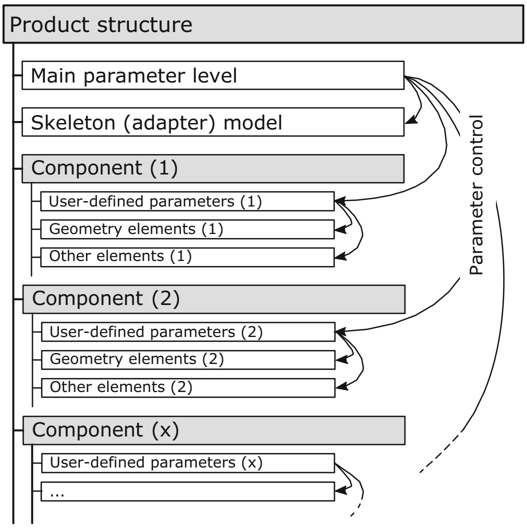

Fig. 4 Relations in parameter-based assembly design based on Hirz [12]

The parameterization of geometrical data requires a separation of geometry representation and its controlling parameters. This results in a broad field of application for problem-specific design tasks, in which the parameter-based control can be used. Today data interfaces, the integration of catalog and knowledge-based functions, and the possibility of macro-based procedures are state of the art in CAD programs. Based on parametric product models, a highly flexible development process is possible in product development [12].

These presented parametric models have so far been used primarily for physical products and have not yet been applied to PSS. A complete and equitable integration of service into the models is a major challenge, but it is necessary if a parametric model should be used for the model-based configuration of PSS.

For the implementation of a parametric PSS model, it is promising to examine the approach of Steinbach (presented in Sect. 4.3) in detail.

4.3 The Extension of Steinbach's Approach

Steinbach's work [29] is based on the objective of describing PPS in a way that both the requirements of the customer and the needs of the developer are respected. To achieve this, a structure must be established in which the PSS is depicted in such a way that both product parts and service parts are consistently described on a common basis.

Therefore, the definitions of characteristics and properties from Weber's [37, 38] Characteristics-Properties Modeling/Property-Driven Development (CPM/PDD) approach are adapted to PSS. The approach of Weber models products from a developer point of view (the characteristics (C_i) level) and from a customer point of view (the properties (P_i) level). These are connected by relations (R_i) which are restricted by external conditions (EC_i) (schematically shown in the upper part of Fig. 5). Figure 5 shows besides the schematic representation of Weber's approach an example which is used in the following to explain the idea of the CPM/PDD approach.

The example contains a hollow shaft which is assumed to be supported at both ends and is loaded with a force. The properties, which contain the important information for the customer, model the product from the customer point of view. Properties in the example are the force (F) on the shaft, the deflection (W) of the shaft, and the weight. They are only indirect influenced by the developer. The characteristics model the product from the developer point of view and can be controlled directly by the designer. In the example the characteristics are the length (l) of the shaft, the inner (d), and the outer diameter (D). The properties and characteristic are connected by the relations, which are represented in the example by the equations for the deflection (W, Eq. 1) and the weight (G, Eq. 2):

$$W = \frac{F \cdot l^2}{48 \cdot E \cdot I} \quad (1)$$

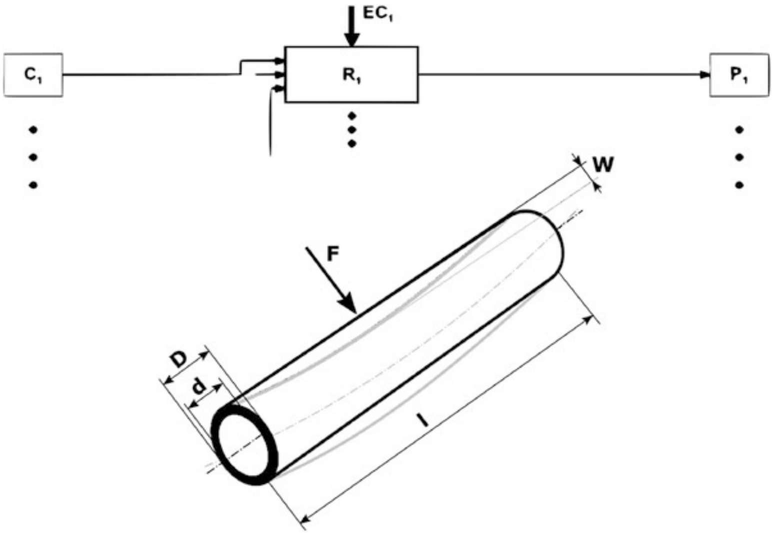

Fig. 5 Example for the CPM/PDD model

$$G = \pi \cdot \left(\left(\frac{D}{2}\right)^2 - \left(\frac{d}{2}\right)^2\right) \cdot l \cdot \rho_{\text{material}} \tag{2}$$

For the deflection the inertia (I) is needed which is calculated with Eq. 3.

$$I = \frac{\pi}{4} \cdot \left(\left(\frac{D}{2}\right)^4 - \left(\frac{d}{2}\right)^4\right) \tag{3}$$

$$W = \frac{F \cdot l^2}{48 \cdot E \cdot \frac{\pi}{4} \cdot \left(\left(\frac{D}{2}\right)^4 - \left(\frac{d}{2}\right)^4\right)} \tag{4}$$

The last part of the CPM/PDD model is the external conditions which model the given parameter and the boundaries of the solution space. External conditions in the example are by norm given diameters, so the developer is restricted in his choices. Another external condition in the example is by norm the given materials for shafts which influence the density (ρ_{material}) and Young's modulus (E) in the equations and due to this the relations. The diagram of the example is shown in Fig. 6.

Of course the assignment of properties, characteristics, external conditions, and relations can shift, in case of changing scenarios. For example, the length of the shaft could also be a property (if it is important variable for the customer), or the length can be given by external conditions (if the position of the bearing is fixed). So the CPM/PDD is a tool which has to be adjusted for the particular scenario.

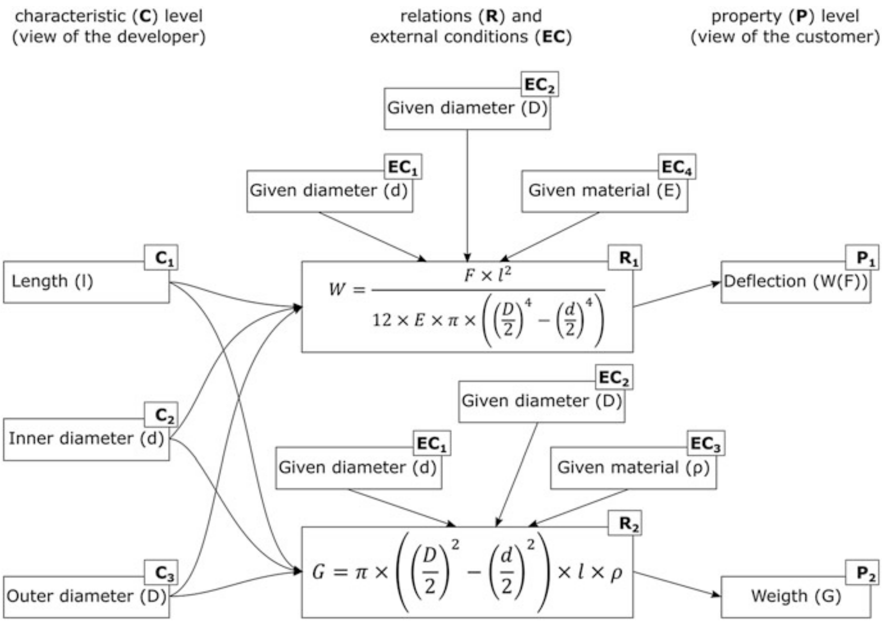

Fig. 6 Diagram of the described example

Steinbach transferred the CPM/PDD approach to PSS to define and visualize the differences between customer requirements (properties) and controllable parameters (characteristics) as well as their relations. He extends the model with the idea of internal relations of product and service parts which could also be visualized. A schematic representation of the PSS model can be seen in Fig. 7; the figure already shows the extended representation with the parametric CAD model.

On the left side, the diagram shows the information for the parametric model, which are mainly the relations between different product and service parts. These parts are shown in the second column, followed by the column containing the relations among characteristics and properties and external conditions. The diagram is completed by the properties, which are displayed on the right-hand side.

This property level includes the customer requirements and is divided into different property classes. They are partly linked by relationships to the characteristic level. The property classes are influenced by the characteristics and process classes of the characteristic level. In addition, the relations can also be influenced externally. This is included in the model by the external conditions (EC). EC formalize restrictions of the possible solution space, e.g., due to technical requirements or economic considerations. The characteristic level includes product and service parts in which product parts are subdivided in characteristic classes and services in process characteristics. The internal relationships of the PSS exist among product and service parts, as well as among their characteristics [29].

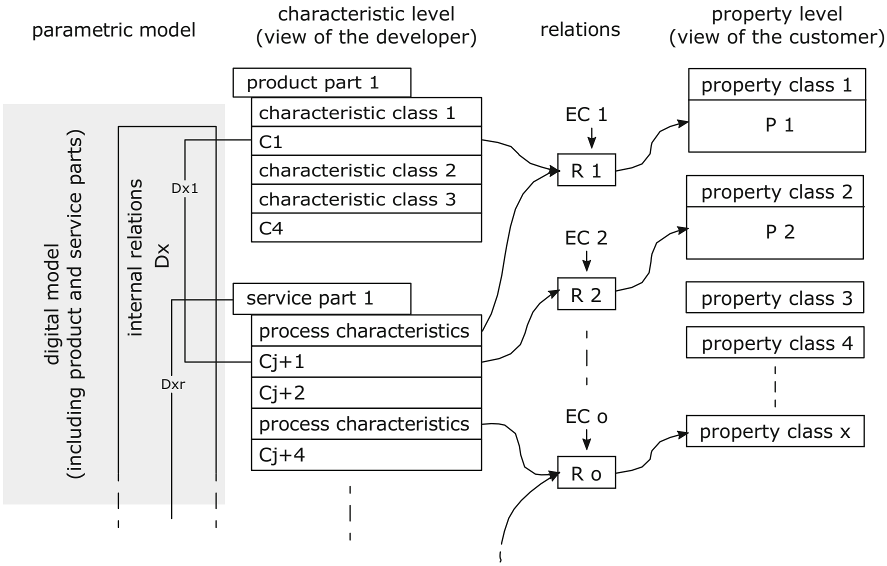

Fig. 7 Concept of a PSS model based on the approach of Steinbach

With this representation, an abstraction level can be found on which the entire system is mapped. In addition, relationships between different product and service elements are identified and documented as internal relationships [29].

For a better understanding, an example of a PSS will be described related to this model. As the example an assembly line PSS is used. In this PSS the supplier provides the customer an assembly line, including the monitoring of the continuous work and the responsibility for the repair and maintenance. The production line is delivered with parts and ends up delivering the assembled and ready-packaged products.

On the property level, the PSS is presented due to different property classes which include the customer requirement like operating costs, the output per hour, or a guaranteed maximum downtime in case of technical problems. The characteristic level consists the product and service parts of the PSS and their characteristics. The characteristics of a product part is, for example, defined by the used components for the machines and how they are assembled as well as characteristics like the output per hour (which is connected through the relations to the property level and through the internal relations to other product or service components).

For describing the relations, external conditions and internal relations, the event of a technical problem is used. In case of a technical problem, the supplier guaranties maximum downtime. This is related to different product and service part characteristics, and these relations are influenced by external conditions. For the product part, for example, the used components for the machines (which have to be exchanged) are related to the downtime, and this relation is influenced by external conditions like part availability and delivery time. For the service part, for example, the man-hours or the level of education of the service technicians (working speed on complex problem) is related to the downtime, and this relation is influenced by external conditions like the maximum available man-hours or a maximum time during the day in which the service technicians have access to the machines.

The last part of the model which is explained in an example until now is the internal relations (D_x) between different products and service parts of the machine. These internal relations are very promising as a starting point for a parametric CAD solution for PSS. In the given example, the internal relations are connecting dimensions between different product parts but also relations between service and product like the correlation of the complexity of the used components for the machines and how they are assembled and the level of education of the service technicians.

The implementation in a data model that is comparable to models of current CAD systems is missing or at least not documented. Since Steinbach has already published his approach 15 years ago, one reason for the lack of implementation could be that the CAD systems at that time had not reached the current standard and an implementation was not possible. Moreover, the application of the approach is documented only in a very simple and theoretically constructed example, which leads to the question whether the approach can also be applied to examples with higher complexity or other areas and thus can be used as a generally applicable approach.

The approach provides a good theoretical foundation for further research on the representation and modeling of PSS. It helps to capture the PSS system and to sketch it in an integrated way.

4.4 Limits of the Approach

The developed approach can be used for the initial development of a PSS because it supports the developer to document the entire system of a PSS and allows the developer a free parameter-based solution space design. Thereby the approach supports a coequal development of product and service components according to the first basic requirement for a PSS formulated at the beginning of the paper. Also the second basic requirement for a PSS, the integration and addressing of individual customers in the development process, can also be achieved by developing a configurator based on the model.

However, when considering the third basic requirement, the monitoring of the customer requirements during the whole life cycle of the PSS and the adaption of the PSS with respect to changing customer requirements, the approach could be used, but with respect to economical reasons, an adaption and extension could be useful.

The limit of the approach is reached when, during the use of a PSS in the life cycle, the system no longer exists purely virtual, but also a real PSS in addition to the digital twin (the digital/virtual image of the PSS). This real PSS often contains not only the service but also physical product parts, which can with respect to economical reasons not be unlimitedly modified. In case an unlimited modification is not economical, these physical components can only be configured restrictively. This requires the system to be modified and the constraints imposed.

A possible solution to this problem is to transform the PSS model after the initial development into a model, which is no longer completely parametric, but rather a rules-based and modular model. The approach of Weber already provides with the external conditions (EC) a promising possibility to model such restrictions.

According to Krause [14], the flexibility of modular products during the life cycle resulting from the exchange of modules can be an advantage for the customer. This statement agrees with the part of the second basic characteristic of PSS, which has brought the parametric approach to its limits. Therefore an idea is presented below in order to extend the approach of the parametric model that the model is transformed into a modular model during the life cycle.

4.5 The Extension by a Modular Model

In the development the PSS is built as described in the parametric approach. Once the initial development has been completed and the PSS is implemented, the digital model is transformed into a modular product structure. The representation of the modular structure can be seen in the Fig. 8.

To get to this, the figure which displays the parametric model can be rotated ninety degrees, so the property level corresponds to the PSS main block because the appearance of the PSS level will still be described by the property level. This level is linked to the characteristic level through the relationships (influenced by the

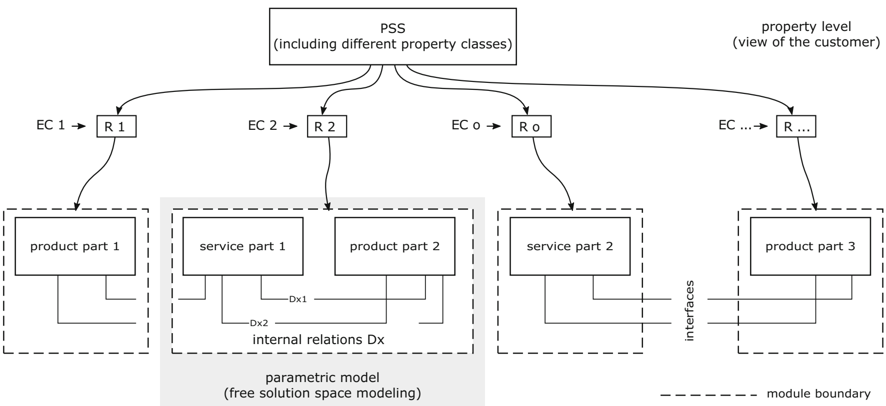

Fig. 8 Modular representation of PSS

external conditions, EC). In this level are the modules of the PSS located, which can consist of several or single product and service parts. The individual modules span separate solutions spaces for themselves in which parametric models can be used again.

The internal relations from Steinbach's approach will also continue to exist when several products and/or service parts are combined into single modules. If the internal relations cross module boundaries, the interfaces between the modules, which were already described in Sect. 3.4, must be defined at these points. These interfaces are important limitations for the solution space of the respective modules.

Transferring this approach on the used example of the assembly line, one part of the line (including the machine as well as the associated monitoring of the continuous work and the responsibility for the repair and maintenance) could be seen as a one module. This module can be modified in case of changing customer requirements or external conditions. In the example the last module contains the packaging section of the assembly line. The case of a changed marketing strategy of the customer (changes on the property level) or new legal requirements (change of the external conditions) leads to a need of an adjusted module. With the defined modules, it is possible to build in such a module a new parametric solution for the individual needs of the customer in a free solution space which is only restricted by the boundary condition of the interfaces to the other modules of the PSS.

5 Conclusion and Further Research

In conclusion, the research results presented in the paper are briefly summarized, and a subsequent outlook on further research is given.

5.1 Conclusion

In this paper existing approaches of developing and configuration of PSS were analyzed. Furthermore aspects of parametric models and modularization were discussed, and the need of a parametric model for the PSS development was shown. Based on this an existing promising approach was presented; two essential extensions for this approach were discussed. Thereby an approach of a PSS development based on a parametric model was created and extended with a modular model for the using phase. This approach was explained on a theoretic example of an assembly line. The research results presented here represent the current state of research, which must be continued by further deepened.

5.2 Further Research

In the beginning of the paper, it was shown that the presented research takes place in the third stage of the DRM. In the fourth stage of the DRM, the evaluation of the developed methods takes place, which must be done in any case in order to prove the established theses.

However, further steps should also be taken in method development to detail the models and standardize the procedure of the model use. Furthermore, for example, a CAD support for the PSS development has to be worked out, and the translation of the PSS into a modular structure must be deepened and evaluated by means of more examples from different application areas.

Since the MC's research field already contains deeper insights into modular product structure, it is also necessary to examine in more detail how far PSS research can benefit from MC's awarenesses.

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Demand Engineering in Mass Customization Using Data-Driven Approach

Rui Xu, Shuhui Qu, Ying Liu, and Jie Wang

Abstract This paper proposes a general process framework of demand engineering as a significant platform of connecting requirements specification as one side and smart factory as the other, which can be applied to all industries. Our framework performs a sequential methodology to solve existing and prospective mismatching problems between two sides. This mismatching misperceives requirements of the market and simultaneously induces huge waste of manufacturing resources, thus severely hampering the industry transformation into Industry 4.0. Affected by the diversity of industries, the requirements to what degree of transformation also varies. Therefore, different industries must clarify their demand for demand engineering.

Keywords Demand engineering · Industry 4.0 · Mass customization · Process framework · Mismatching · Requirements · Smart factory

1 Introduction

Recent research in the consumer market has shown that a large and growing population of consumers desire customized product that not only with higher quality but also meet their exactly need. To fulfill the requirements desired by the customers, and thus be competitive in the marketplace, companies strive to differentiate their product and believe that a product family with larger variety is more likely to dominate the market than the others [1]. However, customization (individually, precisely) contradicts mass production (quickly and inexpensively) when they are implemented in traditional factory. As a consequence of fulfilling mass customization, the conceptual model of smart factory is developed, which joins

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the idea of Industry 4.0 and the recent technological achievements of intelligent and automated production systems, with an aim to improve the efficiency and reduce the cost [2].

The realization of Industry 4.0 is through the technological evolution from embedded systems to cyber-physical systems [3]. While this process requires the most advanced technologies of automated production, big data processing and modeling, the integration of different activities of the whole market and effective communication between requirements specification and smart factory are also the necessity that prepares the arrival of Industry 4.0. After years of effort on the discussion and the development of smart manufacturing and Internet of Things, which are the major components of Industry 4.0, several models and frameworks have been proposed to solve problems, nonetheless, only focusing on either side of the two sides [4]. Although a few techniques have been developed to try to build the connectivity between two sides, their domain is constrained to specific industry and not feasibly extended to the scope of all industries [4, 5].

As a consequence of implementing the collaboration platform for both sides, demand engineering is developed to assist smart factory to precisely perceive and classify individual requirements. Since demand engineering can avoid mismatching problem at the beginning, it secures correct inputs of the product configuration and manufacturing process in a factory. Furthermore, the subsequent matching and optimization process have been carefully engineered to significantly reduce the waste of manufacturing resources and maximize the satisfaction of the market, and therefore common issues in the factory caused by mismatching, such as excess capability, high inventory level, and over-competition, can be alleviated or completely solved as the technology of demand engineering matures.

Our members in the Center for Sustainable Development and Global Competitiveness (CSDGC) reach a consensus that the proposed framework must be flexible and efficient enough to fit the context of all industries and correspondingly fulfill the variants of requirements rather than one that is strictly determined and extremely narrowed. Additionally, it must be capable of not only understanding the customers' expectation for existing product but also predicting demand of future product.

2 Related Work

Przemysław Zawadzki and Krzysztof Żywicki [2] present concept of smart design and production control, which could potentially improve the efficiency of smart factory and thus the competitiveness of an enterprise. Most attention is drawn on the techniques for rapid design and production, as well as the cost reduction of mass customization. The authors fully understand the risk of investing on advanced technologies such as dynamic scheduling on production control and CAx,VR, and RP on product design, whose improper implementation or failure will result into serious loss of manufacturing resources. Hence, a company-level knowledge-based systems is highlighted as the backbone to support the implementation of advanced technologies. Despite the knowledge-based system is likely to avert failure in the smart factory with the support of previous experience, it cannot correct the error if the initial inputs such as customers' expectation for the product is misunderstood by the supplier and thus mismatching problem occurs. One thing worth noting is that the authors assume their systems must be capable of processing large amount of data and synchronizing material flows during the production, which are the same assumptions that we made for our framework [2].

Requirements engineering is a set of systematic approaches that help software engineer to identify and communicate the requirements (purpose) of a human-centered dynamic system that collaborates and integrates hardware and software (software-intensive system) and the contexts in which it will be used. That is, requirements engineering, similar to demand engineering, performs as platform connecting real-world needs of users, customers, and other constituencies affected by a software system and the capabilities and opportunities afforded by software-intensive technologies. While requirements engineering build a basic structure that specifically but narrowly focuses on clarification of requirements with user involvement in the domain of software-intensive system, its requirements refinement driven by viewpoints of different stakeholders inspired us to carefully engineer the inputs obtained from requirements analysis into the process of design and production in smart factory [4].

Following the basic structure of requirements engineering, a process framework for requirements analysis and specification is proposed by Enrique García Alcázar and Antonio Monzón [5]. It can be used as a reference for driving concrete requirements engineering process. Realizing the flow path of requirements engineering activities is not a linear but cyclic and iterative process in a loop of requirements elicitation, specification, and validation, building a problem domain and fitting the user demand in that context become the foundation of the process framework. Typically, static object-oriented models are used to capture the information that build a common understanding of the problem domain, and facet model, which are borrowed from the field of domain analysis, is performed to graphically represent the structure of problem domain. A great contribution to information capturing and problem representation has been made by the proposal of the process framework, whereas it is still constrained to the field of software engineering. Furthermore, it is not vigilant and flexible to evolution of requirements even in a single domain because the static representation cannot keep tract of the change of context information. Suppose new information with different structure or context feeds into the system, the information capturer which only fits the older model is more likely to misinterpret the structure or context of the requirements. Hence, there is no chance for such method to predict the requirements of future product, which are subject to change dynamically.

The previous studies are biased to either prospective of smart factory such as mass customization or the other side, for instance, requirements engineering in a single industry such that mismatching issues inevitably and consecutively occur during the implementation of Industry 4.0 in practice. The induced problems by such discrepancy will be settled by applying the process framework in the next section.

3 Methodology (Framework)

In order to support demand engineering regarding to mass customization of products, we thus propose a process framework. The framework was inspired by requirements specification by software engineering projects [5]. This framework, however, is not only limited to the analysis of software product but, more importantly, also acted on physical product, in which software serve as one of the components. Moreover, the framework analyzes the requirements through the entire life cycle of mass customization [6]. In manufacturing area, products, which need to be customized to maximize the fulfillment from different stakeholders, have the large dispersion in the objectives and styles. Thus, this demand engineering framework aims to systematically describe the requirement as well as demand from different stakeholders and provides solutions to find customizable product design with appropriate, feasible technologies to serve these requirements and optimize the products. The development of demand engineering is not a one-shot process. Instead, it is developed iteratively in a spiral model with a sequence of waterfall increments. Thus, in this work, we present this framework, which is divided into four processes for product development, ranging from the demand identification of current market, matching current available techniques with different demands, product design optimization based on currently available resources, and the validation of the products design. With each process, we suggest the techniques that we have found most useful to obtain good results, as well as the way to apply them in practice. Obviously, there also exists other methods could be used. However, the key point is to illustrate the objective of each process instead of the detail of each technique (Fig. 1).

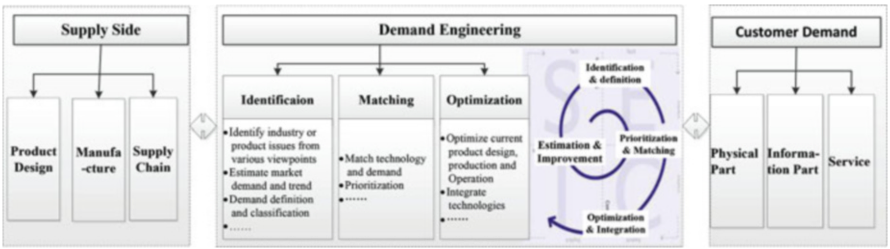

Fig. 1 Structure of the process framework of Demand Engineering

3.1 Demand Identification

In general, for demand engineering activities, there are two possible scenarios:

(a) For an existing product, customers require modification on different parts and expect improvements on several aspects. Engineers need to find reviews, comments, and trends to understand customers' expectations.
(b) For a potential, non-existing product, engineers need to understand pain points of customers and provide feasible solutions based on current available technologies and resources.

Both cases could apply our proposed framework, with slight modifications. Thus, the demand identification could explicitly recognize demands from a diversity of the sources of demands, cluster these demands, and organize the demand information in a formed way, which provides great benefits for further demand management. For instance, the contribution from each stakeholder could be identified; conflicts between stakeholders could be easily found.

Viewpoints The idea of viewpoint-oriented approaches, originated in software engineering, is a way of organizing the requirement from different viewpoints [7]. These approaches try to tackle requirement analysis from different perspectives and provide a more comprehensive understanding of people's need. By analyzing the ideas, perspectives, and relationships at various levels of detail, the viewpoint-oriented approaches support manufacturers/designers explicitly recognize the requirement from different perspectives, which provides possibilities to management and organize the diverse information.

There are typically two types of viewpoints [8]:

(a) Direct viewpoints that represent customers or other systems that interact directly from the system and send information, such as reviews and other data back to the system.
(b) Indirect viewpoints that represent stakeholders who do not interact directly with the system but would have influence in some or all of the services to be delivered by the system.

Each indirectly viewpoints may have a relation with the system based on its needs and interactions with the system. Based on our understanding, we identify several contingent perspectives in both direct and indirect viewpoints. In the industry, these perspectives include (1) direct customers, (2) the manufacturing companies, (3) designers, (4) social culture environment, (5) policymakers from politic as well as financial side, etc.

Identity Product Demand from Heterogeneous Data Sources In this step, we gather information regarding the proposed and existing systems from different viewpoints.

The direct viewpoints could be obtained from the critiques, verified customer's review, and feedback on previous products or similar products. However, in manufacturing area, depending on the industry, this information might be hard to widely obtain. Also, potential or target customers' expectation is concealed and focuses on different aspects of a product. However, as the development of technology, microblogging and social networking services, which has become popular recently, provides an alternative to gather information. In the USA, more than 160 million users around the world are using Twitter to remain socially connected to people [9]. In PRC, it is estimated that more than 130 million users are active on Weibo everyday [10]. These tools enable rapid news information publishing and propagation, especially for the news information. Various works have been done toward trending topic analysis that could understand hot topics related with specific products, as well as technologies to understand and predict the demand of a products. One of the most important works is latent Dirichlet allocation (LDA) that is widely applied for topic modeling [11]. The original LDA is independent with time. Thus, several topic models with temporal information are proposed. Blei and Lafferty [12] further proposed discrete-time dynamic topic models (DDTM) by using variational approximations based on Kalman filters and nonparametric wavelet regression to perform approximate inference on topics. By using this model, they successfully analyze the trend of research in several important journals. Compared with DDTM, continuous time dynamic topic model further applied the Brownian motion to model the latent topics through the sequentially collected documents [13]. Wang and McCallum [14] presented a "topics over time method" (TOM) based on LDA that considers the mixture distribution over topics along with time. Grant [15] further proposed an online inference model depending on the time frame of tweets for topic modeling on Twitter that could be used for real-time Twitter trend analysis. By using existing topics, Lu and Yang [16] applied moving average of convergence-divergence as an indicator to predict the trend of topics. These methods thus generate a pool of demand for products. To be mentioned, there already exist various works that use customer's review only to improve their service and product design.

Apart from the stakeholders, there are many sources for indirect viewpoints. Here, we list a few: the company's operational report, political factors, financial support, domain standard, as well as competitor's strategies. Depending on the complexity and difficulties, various methods could be applied to retrieve these types of information. The information should not limit to text, but other formats, such as graphs and references, should be captured as well.

Demand Classification and Organization The demand documents are collected from different sources and various stakeholders with focuses on diverse aspects. Thus, before we start to provide a solution for the product. One of the key steps is to clarify the problem by distilling the information relevant to the product, cluster information and organize them into an understandable representation. Also, in some cases, stakeholders always express requirements in their own terms [4]. It is thus important to clarify the common understanding of expectations, problems, concepts, characteristics, as well as relationships. Also, unifying the vocabulary and definition with regard to these objects is important as well. There are several language processing tools to aid information classification. For instance, Word2Vec is proposed by Mikolov [17] to learn distributed vector representations that could capture syntactic and sematic word representations. After that, word embedding is used as an enhancement for those nature language alogirthms dervied from ditrbuted vectors to better represent sentence/phrase correlation [18]. By using the representation learned from these methods, the demands could be further classified. This step helps to group related or similar demand and organize them into coherent clusters. The classified demands then are organized and put into an object-oriented model [19], which provides great convenience for management.

3.2 Product Function/Matching

The demand list provides the description of what the product needs to be fulfilled, and its specifications. Not all demands on the demand list, in most circumstances, could be accomplished. In practice, demands from different stakeholders may conflict with others, which provide both opportunity and challenges. Decisions have to be made under these circumstances, such as tradeoff across selection of specifications. Also, some demands are not realistic and can hardly be fulfilled due to the restriction of technology, cost, production limit, etc. Thus, under the matching step, demands from various perspectives are prioritized and would be transited into required functions to be fulfilled based on currently available technologies. This matching process between the demand and functions needs to be defined explicitly since the demand usually has multiple perspective of view which can be reflected on the number of dimensions of required functions.

With viewpoints captured from a large variety of direct and indirect data sources, the volume of product variants in a demand list can never be underestimated. It is not hard to imagine the total number of product variants increases exponentially with each added class of variants. For instance, 30 classes of variants of an arbitrary mode of Ford in a demand list, which is tiny compared to the number of most common features of a car, would result into one trillion possible variants with the assumption of only two variants of each class. This number is obviously much larger than any mode of Ford sales. While higher variety of products would potentially increase sales, manufacturing process prefer fewer classes of variants. In machine learning area, class of variants is known as dimension. A dimension-reducing technique is entailed on the mapping process from demand list to the domain of required functions. To further remove the less important classes, prioritization process could be done either before or after the mapping process. It is worth noting that the representation of variants in demand list is a mix of words and numbers so that regularization needs to be performed beforehand. Since importance ranking is associated with supervised learning, a supervisory signal or response is needed to indicate the contribution of each class of variants. We suggest to use the latest sales data of existing product which can fulfill the variants of demand. By using matured unsupervised learning method such as principal component analysis

(PCA) in mapping process, a subset of correlated variants can be obtained instead of a full demand list of variants. However, we must interpret the derived subset via recovering the meaning from the original demand list. Ideally, the elements in the domain of required function are the subset of PCA mapping from the demand list. But they are hardly matched in reality. Therefore, representation of the elements in subsequent domain or mapping function should be carefully engineered. Considering the technical feasibility that reflects back on the domain of required function, the mapping of some variants that are more preferred than expected but not realistic is likely to fail. Without removal of such redundant variants, erroneous information would propagate through the process of subsequent demanding engineering framework. To secure a valid information propagation, the mapping result must be fed back into the original demand list to eliminate the unexpected variants that are not acceptable to the system. Iteratively conducting such corrective action can significantly reduce the error in following operation.

3.3 Design, Process, and Logistic Optimization

In previous step, the matching process generates solutions in the form of specification of functions that meets the most important stakeholders' expectation. Based on the specified functionality, the main focus of this step is to find technical feasible design parameters that could fulfill these functions. This is also called as platform-based product family design. This step involves typical decisions regarding product family design and configuration.

Along with decision with regard to the design parameters of the product, the processing variables and logistic variables could also be considered as part of the design phase since the demand from production and logistic stakeholders also need to be considered. The mapping from design parameters to processing variables deals with the process design task, which could facilitate the analysis of the influence of current production on the manufacturing and production planning within existing process capabilities and utilize repetitions in tooling, setup, and equipment [1]. The mapping from design parameters and processing variables to logistic variables handles the supply chain management, which could address the supply chain-related issues of product production fulfillment, such as supply chain configuration, resource allocation, supplier management, and supply contracting [6].

3.4 Verification

The design phase helps to connect each stakeholder's demand to design parameters that could technically fulfill the demand, processing variables that enable the product being processed successfully as well as logistic variables to ensure the supplies as well as deliveries. In order to confirm that most required demands and their related functions have been adequately taken into account in previous processes, verification needs to be performed after the design to allow retrospect of decisions [5].

During the demand engineering process and system development, the demands from some stakeholders might change. Also, during demand identification process, information is inevitably incomplete and inconsistent, new demand might emerge during the process as business needs. Thus, the demand engineering process is not a linear but a spiral process. After each time, all activities' process needs to be performed iteratively.

4 Scope of Use

The goal of demand engineering is to improve the efficiency of mass customization for all industries and fulfill their customers' need, whereas not every industry has a strong desire to mass customize. This is because, for certain markets, the requirements of product never change or change periodically or geographically which are very predictable. Industry in such locally and temporarily stable markets generally has no desire to develop strong supply chain since factory is built close to local market. For instance, the product of cement industry is the necessity for modern urbanization, specifically building construction. Although requirements for cement change passively with the living environment, such as local precipitation, temperature, inland, or coastal which set different standards for cement, they are stable and determined in a geological time within which the living environment is not likely to change. Hence, implementation of demand engineering has little benefit in cement industry. Conversely, furniture industry, which is associated with cement industry to make real estate, has high demand for mass customization. People evaluate the value of furniture from different perspectives, for instance, functionality, esthetics, material adoption, or even the fame of designer. These requirements are unstable with different groups of population. Even for a single person, his/her taste of furniture is unpredictable for various periods. Those various and dynamic factors contribute to the high demand of mass customization in furniture industry and therefore induce an effective use of demand engineering.

We present the customization needs of several industries on a graph regarding their proportion of overall GDP of China in 2016 and level of the technical development in a 3D plot in Fig. 2. For convenience, the axis of "proportion of GDP" is simply divided into three quadrates highlighted with color black, blue, and red, respectively. Note that the GDPs of industries in the same quadrate are not exactly the same rather they are closer to each other compared to other quadrates. "Technical development" is not strictly defined or quantified, primarily taking new technology adoption rate and R&D investment ratio to revenue. "Customization need" is measured with number of demand variants from the perspective of customer. At current stage of this research, we are meant to show the relative importance and overall trend of industries rather than quantitative analysis. Interestingly, customization needs are

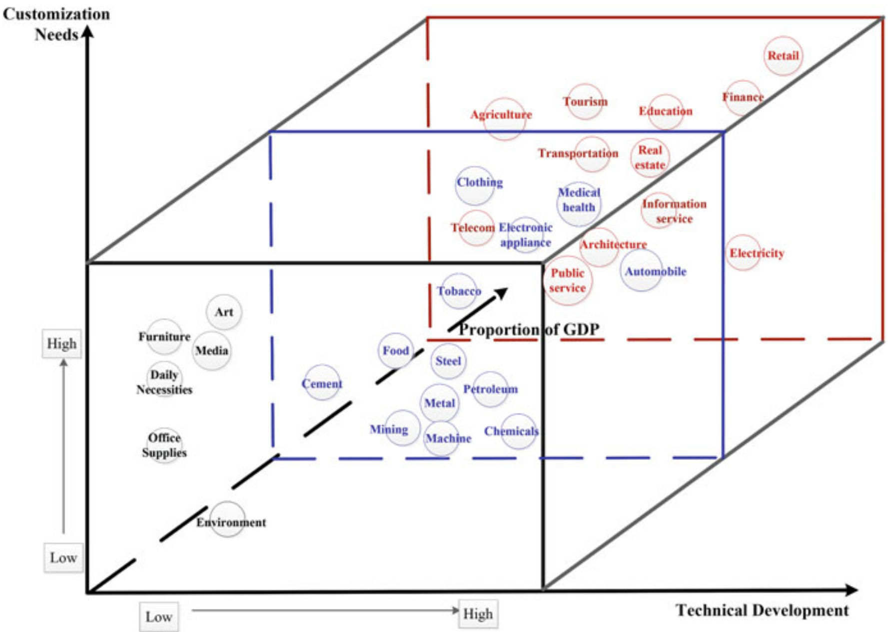

Fig. 2 Customization needs in terms of proportion of overall GDP and technical development of China in 2016

not related to either one of the factors, while we discovered that industries such as mining, petroleum, machine, and tobacco have lower level than the others. Similar to furniture industry, the requirements of product in such industries are relatively stable, whereas industries like retail, tourism, and media have higher level due to the unstable preference of customers. However, this plot cannot portrait the MC potential in a foreseen timespan. For instance, demand of environmental industry is imposed by government agency, which not only raises the bar for existing pollutant but also keeps adding new pollutant into its demand list every year. The number of yearly added regulated pollutant is especially large in developing countries like China due to the increasing concern about environment protection. In addition, environmental concern is expected to be a driven force of increasing customized needs across all industries. That is, the pattern learned in environmental industry can be transferred into other industry and plays an important role in the future.

5 Conclusion and Discussion

This paper proposes the concept of demand engineering and provides its flexible and effective process framework as a key element in a smart factory to support the realization of precise and efficient MC production by primarily using data-driven approach. Without correctly using it on each transition step between two conceptual domains derived from product family design, a high risk of unexpected waste of manufacturing resources and customer loss could be taken and hence severely harms the competitiveness and hinders the transformation into Industry 4.0 of an enterprise. While demand engineering framework is aimed to prepare a tool box of modified data-driven approaches to solve the real problems occurred on the entire value chain of MC, integration of temporal widely used rule-based approaches such as modular product architecture is still beneficial and essential at current immature stage.

Regarding the techniques of data-driven approaches, further research could be conducted in developing a general standard of performance measurement that fits the domain knowledge of MC rather than the conventional statistic test used in machine learning. Leveraging the cost of iterative adjustment within each step and the framework itself, which, as a whole, is a cyclic system, is essentially concerned. Furthermore, the cost must be carefully defined and quantified in terms of not only computational loss but also opportunity cost through the entire value chain of MC. Scalability of the framework is another concern that is not possible to be determined in short time period. With stable performance during a reasonable period of operation on a single smart factory, the framework is then believed to be reliable to deal with multi-factory scenarios in which aggravated discrepancy of the market would significantly affect its performance. Last but not least, a great effort has been made on building pilot research platform with our collaborated partners in different industries so that we can collect real data in the future that is helpful to analyze the performance of the current framework. Only then will it be fully possible to refine the framework according to the result of performance analysis in real situation.

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Adapting Product-Service System Methods for the Digital Era: Requirements for Smart PSS Engineering

Simon Hagen, Friedemann Kammler, and Oliver Thomas

Abstract In the past a lot of work has been spent on creating and improving methods to develop integrated systems consisting of products and services, named product-service systems (PSS). Due to the different disciplines involved in creating and maintaining these systems, e.g. service engineering, product and production engineering or information systems, the interfaces between the stakeholders have to be defined to integrate them and to make them work seamlessly. However, in recent years the concept of PSS shifted, influenced by the still growing impact of smartness and intelligence in the domain of information and communication technology (ICT). The rise of smart products and services led to the enhancement of "smart" product-service systems (smart PSS). This paper identifies, based on recent work and a literature review, methods developed for designing PSS. The main characteristics of the methods found are then analysed with regard to the affects smartness has on them. Knowledge about the smartness aspect is taken from descriptions of smart PSS. The findings are used to derive evidence about the transferability of PSS to smart PSS development methods.

Keywords Product-service system · PSS · Smart PSS · Smart engineering · Smart product · Smart service

1 Introduction

1.1 Motivation and Research Approach

The evolution in value-creating systems has changed a lot in recent decades. The development reaches from separate product- and service-oriented systems to today's

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integrated product-service systems (PSS), which do not consider the separation of products and services anymore [46]. Consequently, not only business models but also methods to develop such value-creating systems changed. However, even established PSS currently are in a new phase of evolution. Due to the continuously growing digitalization, especially in business environments [2], new aspects such as "intelligence" or "smartness" supplement them. Therefore, new terms like "smart PSS" [51] or "smart service system" [33] have been established. However, further research needs to be conducted on the design and engineering of smart PSS [50].

This work contributes to the discussion on the development of smart PSS engineering methods, by analysing existing methods from the field of PSS engineering. In a second step, identified methods are compared to the characteristics of the still increasing "smartness" and "intelligence" in the domain of ICT and deriving indicators about the transferability of PSS to smart PSS development methods.

1.2 Research Background

1.2.1 Product-Service Systems

PSS are rooted in the product engineering and construction theory of the 1950s. During the 1970s and 1980s, the first scientific attempts of service development called "new service development" (NSD) and "service design" were made [11]. Levitt commented [21] "everybody is in service". However, he beard on product-related services, which were additionally offered by companies [12].

With the advent of "service engineering" during the 1990s, the discussion on service development became more important, especially in Germany [11]. During the mid-1990s, the scientific development in German-speaking countries was done in parallel to the American NSD-term but was focused solely on the service, not on the combination of a service with a (physical) product [47]. Nevertheless, the methods used in service engineering research are also rooted in product engineering. This changed during the turn of the millennium when the integrated development of products and services, named "PSS", appeared. While both partial aspects were viewed individually before, it transformed into an integrated view [47]. Figure 1 shows the development schematically.

PSS can be characterized as a marketable bundle of product(s) and service(s), which in combination serve the demands of the user. They can be offered by a single company or an entire group and do not have compulsory, definite product or service components [14, 36]. This fluent transition is shown in Fig. 2. Therefore, the aim is not the one-time sale of a physical product, but rather the provision of a customer solution, which consists of a combination of products and services. The development of PSS is also referred to as product-service systems engineering (PSSE, cf. [11]).

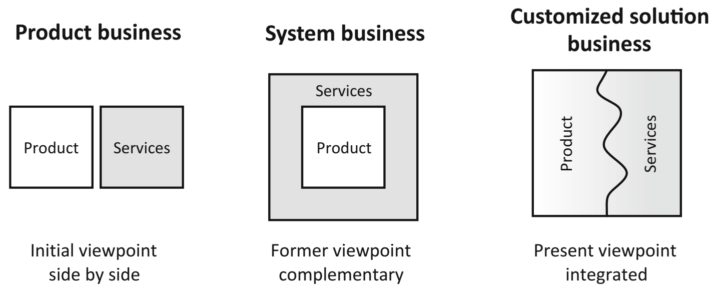

Fig. 1 Paradigm shift in product and service development [43]

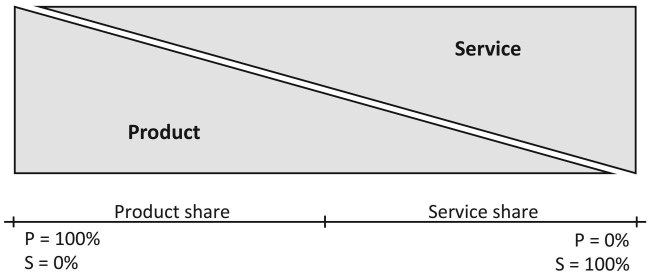

Fig. 2 Distribution of the components in a PSS [36]

1.2.2 Smart Products and Smart Services

In their papers Porter and Heppelmann name digitalized products "smart, connected products" which consist of three characteristics, a physical, intelligent (smart) and connected component. In contrast to traditional products, they add sensors, processors, software and control units. Traditional products only consist of the physical component, which does not enable their own decisions ("smartness") or a connectivity to other systems enabled by components such as antennas, protocols or ports [39]. The author's description is not embedded into a superordinate, result-oriented system. Therefore, there is no direct relation to the PSS definition given in the previous chapter. Anderl, Picard and Albrecht [3] have a similar approach for the description of smart products and appoint cyber-physical systems (CPS) as their predecessor where they emerged from. CPS consist of sensors, actuators and embedded intelligence. The last one is the most important for smart products; it enables them to react autonomously within the communication with other smart products, in particular via Internet technologies [3].

Wellsandt et al. apply the PSS concept to services, which require a supply of a demand-actuated combination of Internet-based and physical services [55]. These are also called "smart service", and sensors and actors of embedded systems are used, whereby the contractor bears the responsibility for the operation of the whole service system during its life cycle. With regard to the authors, the concept of smart services is usually used in product-oriented offerings where a service- and result-oriented offering should be transformed [55].

1.2.3 Smart Product-Service System

The term smart service system or smart PSS describes the development of integrated products and services as well as the digitalization across the system. Valencia et al. explain the new level of PSS, to which they refer as smart PSS, with the "advances in information and communication technology (ICT)" [51]. The "smartness" originates by the use of "microchips, software and sensors, which allows them to connect, collect and process information" [41]. The National Science Foundation (NSF) defines smart service systems [33] as a "[. . .] value co-creating configurations of people, technologies, organizations and information that are capable of independent learning, adapting, and decision-making. Smart service systems, therefore, possess self-detecting, self-diagnosing, self-correcting, self-monitoring, self-organizing, self-replicating, and/or self-controlling functions and capabilities based on data that has been received, transmitted, and/or processed". Abramovici et al. specify smart PSS [1] by means of five main characteristics, namely, a high degree of autonomy, strong human centration, openness and variability of smart PSS solutions along their life cycle, innovative business models and a very high degree of complexity. They describe it as a networked combination of smart service systems and smart product systems, which arose from conventional PSS with their characteristics (sociotechnical system to fulfil customer needs; [1]).

All of the definitions cited above identify the autonomy, driven by data and enabled through ICT, as one key component of smart PSS. This is, beside the diminishing barrier between products and services as shown in Fig. 1, the main advancement from today's PSS. Following Thomas et al. [47], who state that the dichotomy of products and services has been overcome, and Abramovici et al. [1], who claim that smart PSS arose from conventional PSS, smart PSS can be added as a fourth step in Fig. 1. Now both components, smart products and services, should be integrated seamlessly and are enabled and supported by smart and intelligent ICT.

2 Analysis of Methods for PSSE

2.1 Recent Work and Literature Review

During an initial literature review, two publications, which build upon each other, could be identified. The first one already aggregated methods for PSS development from the literature [15], and the second one listed newer ones (up to 2015) and used them to develop a specific framework [30]. Both publications will be used as a starting point to do a literature research to close the gap between the submission of the latter publication (2015) and today. In total 21 process models were considered, 14 resulting from the publications named above and 7 in the literature research. Both contributions featured few more models, which could not be examined due to missing access or were duplicates. We conducted the literature review analogue to [54]. The search term is composed of the terms PSS in various forms and

Table 1 Findings of recent literature and literature review

Source	Author of model	Publications
Gräßle et al. [15]	Aurich et al.	[4–6]
	Lindahl et al.	[22–25]
	McAloone et al.	[27, 28, 45]
	Mont	[31, 32]
	Rexfelt and Af Ornäs	[40]
	Spath and Demuß	[43]
	Thomas, Walter and Loos	[47]
	Weber, Botta and Steinbach	[8, 44, 53, 52]
Metzgeret al. [30]	Boughnim and Yannou	[10]
	Isaksson, Larsson and Rönnbäck	[16]
	Lee and Kim	[20]
	Maussang et al.	[26]
	Niemöller et al.	[35]
Literature review	Boucher et al.	[9]
	Kim et al.	[17]
	Kumar et al.	[18]
	Mengoni and Peruzzini	[29]
	Pezzotta et al.	[37, 38]
	Song and Sakao	[42]
	Tran and Park	[48]
	Zine et al.	[56]

is combined with synonyms for "development" which are used in the scientific environment in English and German. Hence we applied the following string to the databases SpringerLink, Web of Science, Emerald, EbscoHost, Wiley and AISeL [13, 54]: *"("Smart Service" OR "Product-Service System" OR "Produkt-Service System" OR "Dienstleistung") AND ((Engineering OR Development OR Design OR Modelling) OR (Entwicklung OR Modellierung OR Konstruktion))"*

As mentioned before, the period is limited to 2015–2017 as well as a limit to "peer-reviewed content" to ensure the quality of the literature. Furthermore, non-accessible sources were left out, too. The results achieved by the mentioned method were brought together in a list and were consolidated step by step. Double entries were deleted after the elimination of remaining articles by title and further on by abstract. The final contextual view yielding the result of the systematic literature research is shown in Table 1.

2.1.1 Result Matrix for PSS Development Methods

In order to compare the identified methods, we used a concept matrix [54]. Table 2 shows the findings, their origin and characteristics.

The criteria are partly taken from Gräßle, Thomas and Dollmann [15] and Langer et al. [19] and complemented by characteristics we identified during the analysis

Table 2 Result matrix comparing different PSS development approaches

Origin	Attributes	Characteristics	*Aurich*	*Boucher et al.*	*Boughnim & Yannou*	*Isaksson, Larsson & Rönnbäck*	*Kim et al.*	*Kumar et al.*	*Lee & Kim*	*Lindahl et al.*	*Maussang et al.*	*McAloone et al.*	*Megoni & Peruzinni*	*Mont*	*Niemöller et al.*	*Pezotta et al.*	*Rexfelt & Af Ornäs*	*Song & Sakao*	*Spath & Demuß*	*Thomas, Walter & Loos*	*Tran & Park*	*Weber, Botta & Steinbach*	*Zine et al.*
Gräßle	Degree of interaction	Individual	—	—	✓	—	—	✓	✓	—	✓	—	✓	✓	✓	✓	—	✓	—	—	✓	—	✓
		Cooperative	✓	✓	—	✓	✓	—	—	✓	—	—	—	—	✓	✓	—	—	—	—	—	—	—
		Collaborative	—	—	—	✓	✓	—	—	—	—	✓	—	—	—	—	✓	—	✓	✓	✓	✓	✓
Own	Considered stakeholder	Producer	✓	°	—	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓
		Customer	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	—	✓	✓	✓	✓	—	—	✓	✓	✓	✓
		Additional Stakeholder	—	°	—	—	—	—	—	✓	✓	—	—	✓	—	—	—	—	—	—	—	—	✓
Langer	Domains	Product development	✓	✓	°	✓	✓	(✓)	—	✓	°	°	✓	°	°	(✓)	°	—	✓	—	—	—	✓
		Service development	✓	✓	°	✓	✓	—	—	✓	°	°	(✓)	°	°	✓	°	—	✓	—	—	—	✓
		Integrated view	—	—	°	—	—	—	✓	✓	°	°	✓	°	°	°	✓	—	✓	✓	✓	✓	✓
Own	Defined process sequence		✓	✓	—	✓	✓	✓	(✓)	—	(✓)	—	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Gräßle	Process sequence	Linear	✓	✓	°	✓	✓	✓	(✓)	°	(✓)	°	✓	✓	✓	✓	✓	✓	—	✓	✓	✓	✓
		Iterative	—	—	°	—	—	✓	—	°	°	°	—	✓	✓	✓	✓	—	—	✓	—	—	—
		Incremental	—	—	°	—	✓	✓	—	°	°	°	✓	✓	✓	✓	(✓)	—	—	✓	✓	✓	(✓)
		Parallel	—	—	°	—	✓	—	—	°	°	°	(✓)	(✓)	—	—	✓	—	✓	—	—	✓	✓
Gräßle	Customer integration		—	—	—	✓	—	—	—	✓	(✓)	(✓)	✓	—	✓	✓	✓	✓	—	—	✓	✓	✓
Gräßle	Revision of creating process		—	—	—	—	—	✓	—	—	—	—	—	—	—	✓	—	—	—	—	—	—	—
Own	Assembly of reusable building blocks		—	✓	—	—	—	—	✓	—	—	—	—	—	✓	✓	—	—	✓	—	—	—	—
Gräßle	Method recommendations		—	—	—	✓	(✓)	—	—	—	—	—	✓	—	—	—	✓	(✓)	✓	(✓)	—	✓	(✓)
Own	Results usable digitally		—	(✓)	—	—	—	—	—	—	—	—	(✓)	—	—	—	—	—	—	—	—	—	—

<u>Caption</u>: ✓ characteristic fulfilled, (✓) partly fulfilled, — not fulfilled, ° cannot be judged

of the methods. The selection of criteria used in this work is limited to the most essential ones, due to their crucial part in enhancing PSS to smart PSS. If the used ones cannot be transferred for smart PSS, the ones left out are needless to consider.

The degree of interaction describes how the producer of the PSS is interacting with other partners during the development. This is specified by means of the considered stakeholders, which are involved in particular. Which part of the system, product or process or both, is focused in the model is stated by the domain characteristic. If the method proposes a defined queue of processes rather than a loose set of steps or even no guidance in tasks, it is shown by “defined process sequence”. If a certain sequence exists, the process sequence lists in which order this is proposed. The customer integration specifies whether they are actively integrated into the process or just considered as a stakeholder. Whether the process is revised and documented and if intermediate results can be reused in following projects, it is shown by the next criteria. The assembly of a collection of predefined processes, built in previous projects, can lead to an increased efficiency by recombining prepared components. The last two characteristics consider the recommendation of specific methods for developing the product or service part of the PSS and whether the documented results are persisted digitally and can therefore be further used in the execution of the PSS.

3 Results and Discussion

3.1 Influence of Digitalization on Characteristic Occurrences

When comparing the features of smart PSS and smart products with the characteristics of the PSS development methods identified above, several requirements for changes within the methods for purposeful use in smart PSS design can be identified. As a basis for the comparison, we use the characteristics identified in the matrix and the summary of smart PSS from section “Analysis of methods for PSSE” and apply them to the characteristics. The changes described imply by the means of their occurrences. This lets us evaluate the differences on a less abstract level.

The *degree of interaction* will gain in importance, especially due to the increasing complexity of smart products and services. Therefore, appropriate methods for collaborative working will be needed to merge more complex components to one integrated product. Nevertheless, the individual or cooperative methods need to improve as well within one stakeholder, because the development of the specific part gains complexity, too. But, the rising complexity might be reduced by using ICT for the development, when it is already present for the product/service.

The main *stakeholders* considered in the PSS methods will stay the same; eventually the amount of additional stakeholders will increase a bit due to new partners in ICT and their importance. The same applies for the *domains* considered, all of them stay important, and solely the integrated view might gain importance.

In addition, the *defined process sequence* used for PSS can stay the same, only the tasks within the processes will change due to shifting requirements, and the amount of iterations increases because of the rising complexity. But this has no effect on the processes themselves.

Integrating the customer in the development process is not mentioned often in the examined PSS design methods. This is due to the customer-oriented focus of PSS astonishing. Therefore, the relation to the customer and his integration into the design process have to be increased, as Botta stated [8] especially for smart PSS. Due to the increasing individualization of the systems to the needs of the customer, his role in the design process gains importance.

Revision of the creation process, *assembly of reusable building blocks* and the further *digital use of results* will stay the same or increase a bit in terms of meaningfulness and process steps. But the increased use of ICT, primarily in the new products and services, will support them and make them more efficient. The revision can be seen as some form of documentation, which becomes easier, if the intermediate artefacts are persisted digitally. Copies for further steps can be made, and analysing the progresses can be done automatically. The intermediate artefacts can also be seen as building blocks for further developments. For example, CAD (computer-aided design) data of products or digital and executable modelled processes can be seamlessly applied on new projects. The same applies to the digital use of results. Digitally stored process sequences (e.g. in the form of BPEL) can immediately be used to support the execution of tasks, for example, by using them in information systems to support service technicians with process guidance [34].

The last aspect, *recommendation of methods for developing the specific artefacts*, is not, as shown in the matrix, fulfilled by many methods up to now. By the increasing complexity of the products and services, it will be even more difficult in the future to propose suitable but generic methods for product and service engineering in one integrated development method.

3.2 Conclusion

Following an overview of PSS, related terms and their history, we prepared a concept matrix showing PSSE methods and aspects they consider based on previous work in PSSE research and a literature review. Using the matrix and the emerging smartness and intelligence in the field of ICT, we discussed the transferability of PSSE methods to develop smart PSS, adapted from PSS criteria and the influence of the emerging technologies, which enable smart PSS.

Based on the identified characteristics of PSS development methods and the influence of smart technologies, we can in general conclude that most of the characteristics and therefore the methods relying on them will change. Although the capabilities and chances of the new systems depend mostly on the new technology, its influence on the methods to develop the systems is not all-embracing. If a company is using a method to develop their offerings, they do not have to switch to a different approach in general. However, especially with the influence of intelligent technologies, specific aspects have to change.

First, the interfaces between the service and the product need to be extended, to increase the abilities to communicate and collaborate. This is not only important for the artefacts of the system but also for the development process, since it applies analogue for the developers of the artefacts (product and service). However, sometimes the interfaces are not even implemented in the superior PSS method. Therefore, new or improved methods for collaboration for the engineers of the system have to be developed.

Second, the last three characteristics show that beside the effort one has to put into improving the developing methods in some areas, this effort can reduce the work needed in others. In this example the ICT parts are, due to their digital nature, suitable to support the development without additional activities. For physical products the development artefacts usually exist in a digital form [49], in contrast to the service development. In addition, specific methods for developing the product and service share of the system need to be implemented. Referring to Anderl et al. [3], no specific models exist for smart products.

Third, the integration of the customer into the development process needs, in comparison to today's PSS methods and with the substantial role of smart technologies in mind, to be improved. Even more specific configurations, enabled by technology, are feasible but also need to be managed and determined by means of the customer.

Beverungen et al. propose in a recent publication [7] an approach for developing service systems or PSS, called recombinant service system engineering. They suggest creating new systems, with a special scope on the value proposition as well as the system characteristic, by combining features of different existing systems. This method goes in line with the separation of this paper in PSS methods and the smartness aspects and needs further consideration.

Summarizing we can say that smart product and service engineering is progressing. However, the current problem with PSSE, a not fully integrated development of the system with the purpose to offer solutions to the customer, seems to proceed in smart PSS development. According to our results, the underlying methods and frameworks are in general transferable and complementable to smart PSS, but the specific requirements, especially by ICT, need to be integrated with proper methods. With this paper we contributed an overview of scientific PSSE methods and statements regarding the possibilities of enhancements from PSS to smart PSS developing methods. A limitation of our research is that statements about occurrences of the PSS method characteristics are hypothetical and not based in real-life findings.

In our upcoming research, we therefore want to compare our findings with actual systems in practice by conducting interviews with companies, who are in the manufacturing and machine engineering, and offer a value-adding system of their products and services. The goal is to learn more about the as-is situation in practice, derive their criteria for smart PSS and develop a support tool for smart service system engineering.

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Part II
Digital Manufacturing and Industrie 4.0

A Marketplace for Smart Production Ecosystems

Managing Variability of Products and Factories

Deepak Dhungana, Alois Haselböck, and Richard Taupe

Abstract The need for product variability to satisfy the needs of customers means that the process of manufacturing these products must also expose a similar degree of flexibility. In this sense, production facilities (factories) can be seen as product lines of manufacturing services. The focus of this paper is on modeling variability of the products in association with the variability in production requirements – the interplay of which gives birth to a smart production ecosystem. We describe an open marketplace, where product sellers can offer their products with variability, end customers can configure these for their needs, and factories can offer their services to manufacture these customized products. Typically, the equipment used to build up the factory also offers variability; therefore the ecosystem also encompasses equipment vendors and the variability of this equipment. We attempt to bring together stakeholders of a production ecosystem in a marketplace that exploits product line engineering techniques.

Keywords Product and factory configuration · Factory as a service

1 Introduction and Motivation

With the increasing demand for individualized products, the need for flexible production processes, modular factories, and intelligent production infrastructures is also increasing. A smart production ecosystem is a collaborative network of product designers, factory equipment vendors, factory operators, and consumers of the products. The common environment is a marketplace which enables the required interactions. We have outlined the vision of smart production ecosystems in a previous paper [8], where the overall methodology is described as PROFACTO

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Engineering, i.e., Product and Factory Line Engineering. In this paper, we focus on the marketplace of such an ecosystem – in particular the development of models and configuration processes required for the operation of such a marketplace.

A smart production marketplace can be seen as a prerequisite for enabling "anytime anywhere production facilities" of the future. Many research initiatives in this area aim to revolutionize the future of industrial production, e.g., the Smart Manufacturing Leadership Coalition (SMLC),[1] the Industrial Internet Consortium,[2] Industrie 4.0,[3] etc.

Product configuration is a well-established methodology for generating/building individualized products (see, e.g., [12]). Typically, product configuration tools ensure *feasibility* of the resulting product, i.e., its configuration must be consistent and complete. In this paper, we extend the role of product configuration to encompass the production process and ensure *producibility* of the resulting product. This guarantees the existence of a production environment (factory) providing all necessary equipment and manufacturing services to actually manufacture the product. Our vision of a common marketplace for products and production facilities foresees a realization of the ideas based on variability modeling and configuration technologies.

This paper reflects our research in an ongoing effort of establishing a smart production ecosystem which is a prerequisite for a smooth transition toward Industrie 4.0. In particular, we provide solutions for research challenges described in our vision paper [8]:

– An approach to *model factory equipment* based on their production capabilities.
– An approach to *model smart products* considering both product variability and production requirements.
– An approach to *model and configure smart factories* based on the availability of factory equipment.
– An approach to *guide a factory configuration* based on the configuration of the products to be manufactured.

We define the notion of a marketplace as a common environment for interaction among factory equipment vendors, factory operators, product sellers, and end customers. The artifacts/models that are shared through the marketplace and their relationships among each other for coordinated activities are described from the perspective of the responsible stakeholders. We extend traditional product configuration approaches to consider variability of available factories and ensure *producibility* of the configured products.

This paper is organized as follows: Sect. 2 describes our vision of a smart production marketplace by introducing its main modeling and configuration concepts, which are described in more detail in Sects. 3 and 4. In Sect. 5, we evaluate this

[1] https://smartmanufacturingcoalition.org/
[2] https://industrialinternetconsortium.org/
[3] https://www.plattform-i40.de/

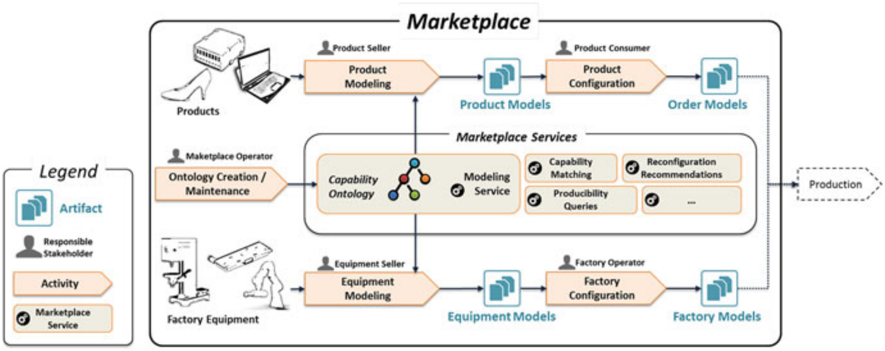

Fig. 1 Overview of the smart production ecosystem depicting the role of a common marketplace for products and production facilities. The actual production process is out of scope of this paper

approach by application examples. After a discussion of related work in Sect. 6, we conclude the paper and describe ongoing and future research activities for smart production ecosystems.

2 Smart Production Marketplace

A smart production marketplace is a common environment enabling the interaction between stakeholders in a production ecosystem (cf. Fig. 1). Such an ecosystem typically involves factory equipment vendors, factory operators, product sellers, and end customers.

2.1 Marketplace Artifacts

Interaction between stakeholders occurs through the publication and sharing of artifacts (models) to the marketplace. In particular, the following artifacts are relevant in our approach:

Capability ontology refers to a common vocabulary used in the marketplace. The operator of the marketplace defines this model and makes it available to other stakeholders as a common language used to model production capabilities provided by equipment and required for manufacturing products. Examples for production capabilities are supply, transport, fastening, drilling, etc.

Equipment models refer to formal descriptions of the factory components that can provide production capabilities in a factory. Equipment sellers publish the set of capabilities provided by their equipment as equipment models. Each concrete equipment is a self-contained modular unit that can execute production operations autonomously. The capability ontology in the marketplace is used to describe the skills of the equipment available in the marketplace.

Factory models refer to formal descriptions of the production facilities. A factory is seen as a specific configuration of the set of equipment deployed in its premises. In the marketplace, factory models are created though the selection and configuration of available equipment models. Typically, a factory consists of production equipment, storage systems, and transport systems in a specific topology. The topology of the factory is an important aspect to consider during factory configuration (cf. Sect. 4.2).

Product models refer to goods that are put for sale to the consumers. Products are seen as digital first-class citizens that maintain their bill of material (BOM), their bill of process (BOP), information about their variability as feature models, and a mapping between the customer view and manufacturing view (cf. Fig. 9 depicting the mapping between feature variability and BOM variability). The materials of the product's BOM use this information to steer their own production and their stepwise transformation toward concrete product instances or product batches (smart products [8]).

Order models are output of the product configuration process carried out by the product consumers. The marketplace configurator presents the features to the consumers and generates manufacturing orders for the factories based on the mappings in the product models. Order models are therefore factory-agnostic descriptions of how the product should be manufactured and can be accepted by all factories that pass the producibility test (see Sect. 4.3).

2.2 Marketplace Services

Various Services are made available to the ecosystem's stakeholders, enabling them to create and maintain the different artifacts.

Modeling service The marketplace keeps track of the capability ontology created and maintained by the marketplace operator. This ontology is provided as a service to product modelers and equipment modelers as the vocabulary understood by the marketplace, e.g., the ontology is used as a service when defining the services provided by factory equipment or when the product is modeled.

Producibility queries are services provided by the marketplace to factory operators and product sellers, enabling them to answer two basic queries: **Q1**: Given a configured product (order model), find all the factories that can manufacture the product. **Q2**: Given a factory, find all products that can be manufactured in that factory. One of the key services required for producibility tests is the **capability matching service**, which can be used to semantically identify matches and gaps between services provided by the factories/equipment and capabilities required for manufacturing a product.

Reconfiguration recommendations can be used both by product designers and by factory operators to learn about potential changes improving their products and services by obtaining answers to two basic queries: **R1**: Given a product model (BOM and BOP), and a factory where it "should" be produced: If the factory is currently not able to produce the product, what are the *recommended changes to the product design* enabling the factory to produce it? **R2**: Given a factory model, and a product model which it should produce: If the factory is currently not able to produce the product, what are the *recommended changes to the factory* enabling it to produce the product?

3 Modeling for the Marketplace

In order to enable smart products and smart factories, they need to be equipped with machine-understandable background knowledge about their properties, their capabilities, and their environment.

3.1 Ontology Creation and Maintenance

The marketplace operator defines the vocabulary to be used by product and equipment sellers as a common language for factory and product specification. Figure 2 shows a (simplified) meta model of *factory* and *product* in UML notation. The main connection between these two parts is the concept of *capability* (often also referred to as *skill*), where capabilities *required* for manufacturing a product are to be matched against capabilities *provided* by production equipment of a factory. Because of space restrictions, we can only sketch the main abstract concepts of the meta model in this paper. All of the classes have various properties and a deep inner structure. For instance, a production operation consists of the following model elements: commands, events, preconditions, postconditions, parameters, materials, constraints, settings, and status.

Figure 3 shows an excerpt of the capability ontology as part of the marketplace vocabulary. The capability ontology contains declarations of all potential capabilities of production equipment. A capability declaration consists of the main parts configuration, constraints, commands, and events. Figure 3 shows an exemplary declaration of the fasten capability, comprising all properties provided by such a skill and, hence, describing its basic functionality and behavior. A fasten capability description is therefore a list of parameters, data types, etc.:

- `Type of fastener`: {screw, nut, bolt, washer, …}
- `Type of head`: {flat, oval, pan, …}
- `Type of drive`: {Torx, slotted, …}
- `Type of washer`: {flat, fender, finishing, …}
- `Screw thread diameter`: {3mm, 4mm, 5mm, …}
- `Screw thread length`: {10mm, 20mm, 25mm, …}
- `Torque of fastening`: 3.1Nm – 17Nm
- `etc.`

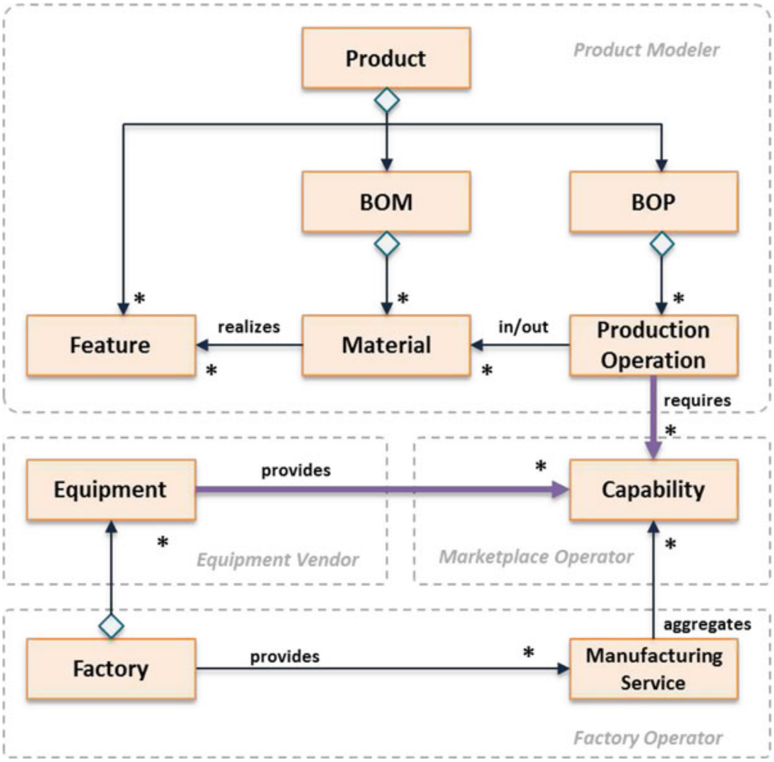

Fig. 2 UML meta model of products and factories, depicting the stakeholders who create the partial models. The marketplace operator models the capabilities, which are the bridge between products, factories, and equipment

Note that these capability declarations do not contain any concrete values, but declarations of such values only and the possible range of values, if it makes sense to specify these. As we describe in the next section, those values are specified in the equipment modeling phase.

3.2 Equipment Modeling

Production equipment such as 3D printers, robots, vacuum or pneumatic grippers, hot-wire cutters, conveyors, drillers, etc. are resources that can be offered in the marketplace and sold as a service. The equipment seller is responsible for specifying all offered production equipment using the vocabulary of the marketplace ontology. The equipment model is therefore another model layer, subclassing the meta model as sketched in Sect. 3.1. It describes all offered production equipment types and their capabilities.

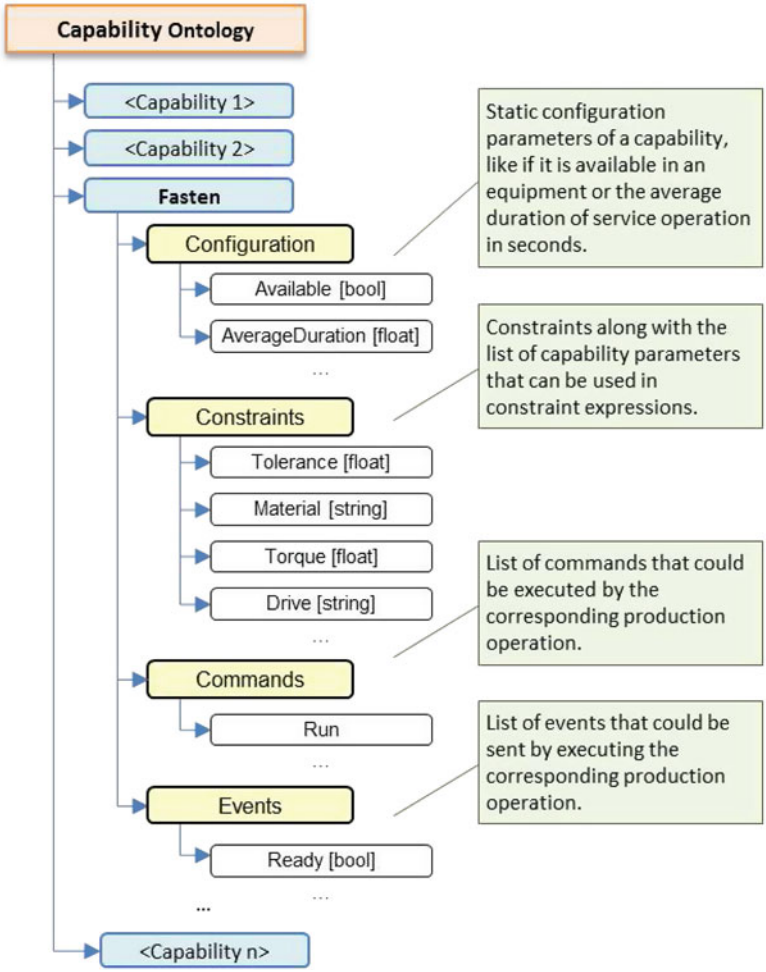

Fig. 3 Sketch of the capability ontology and example of a production capability declaration

Each **equipment** provides a set of production and/or transportation capabilities. *Capability matching* is one of the crucial tasks in computing a workflow plan for processing all production operations of a BOP: for each required capability, at least one matching provided capability must be found. Equipment capabilities are aggregated to manufacturing services provided by the factory. Figure 4 shows the parameter values and constraints of a fasten capability provided by a robot of type XYZ. Concrete values, value ranges, and constraints are specified for each property declared in the capability ontology (cf. Fig. 3). For example, the torque force of this robot type could be adjusted within the range of 6.5–13.4 Nm:

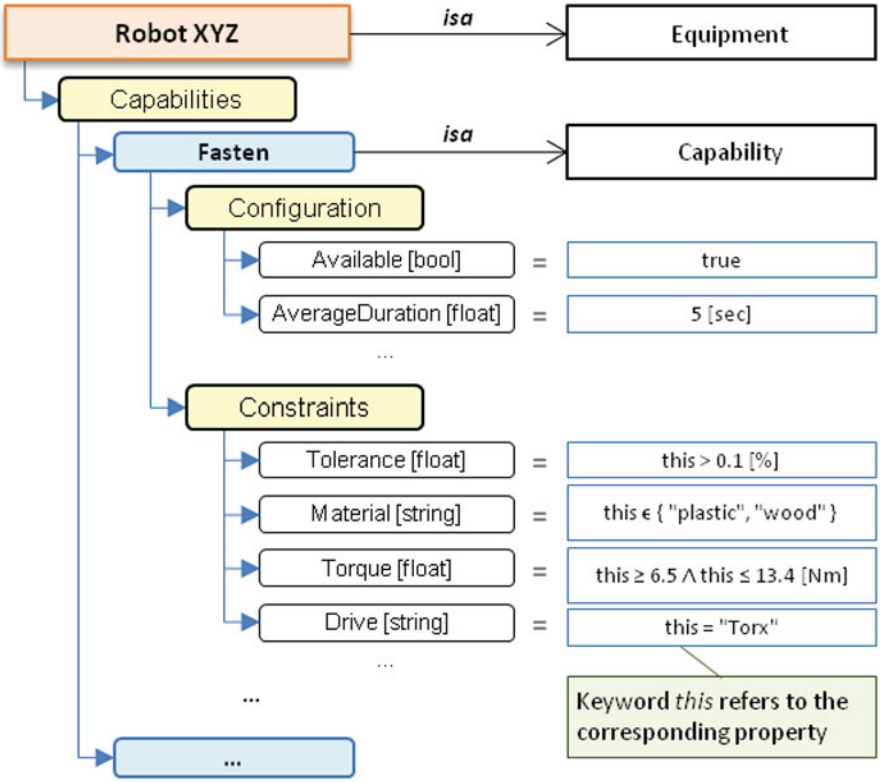

Fig. 4 Example of a fasten capability of an equipment model

- `Type of fastener`: {bolt, washer}
- `Type of head`: {oval, pan}
- `Type of drive`: {Torx}
- `Type of washer`: {flat, finishing}
- `Screw thread diameter`: {4mm, 5mm}
- `Screw thread length`: {20mm, 25mm}
- `Torque of fastening`: 6.5Nm – 13.4Nm.

Typically, a manufacturing service is an aggregation of capabilities which collaboratively implement a complex manufacturing functionality. Modular machines, for instance, offer sequences of associated production steps realized in an optimized way. Another example is *human-in-the-loop* functionality where production segments are provided by collaboration of human and machine.

3.3 Product Modeling

The product model includes both the problem space view (customer-facing features) and the solution space view (BOM + BOP).

Feature modeling: Feature models [16] are a well-studied, standard way to represent the problem space, and reasoning techniques are provided for configuring individualized products from a product line. The feature models for the products in the marketplace are created using traditional software product line engineering modeling tools.

BOM/BOP modeling: From the solution space point of view, the product model consists of a configurable BOM and a configurable BOP. A BOM consists of materials which are typically organized in form of a partonomy. A BOP is a set of production operations specifying all necessary steps for manufacturing a product. A production operation acts on input materials and results in one or more output materials. A production operation may have associated a set of alternative capabilities required for performing the production step.

Such product families are conveniently represented by a tree-shaped structure as shown in the right part of Fig. 7. Each node represents a material, having a sequence of production operations associated. Structural and consistency constraints restrict the potential solution space of concrete products. The production operations specified in the BOP follow the same structure as the description of the services provided by some equipment, with the difference that these capabilities are specified as required capabilities. For example, if a fastening capability is required by a product, the parameters may be specified as:

- `Type of fastener`: {bolt}
- `Type of head`: {oval}
- `Type of drive`: {Torx}
- `Type of washer`: {finishing}
- `Screw thread diameter`: {5mm}
- `Screw thread length`: {25mm}
- `Torque of fastening`: 9.3Nm – 11.2Nm
- `etc.`

Now it is the task of the capability matching service to decide whether the service required by a product is fulfilled by any equipment. This operation is an ontology mapping problem which is described in Sect. 4.

Mapping problem and solution spaces: To allow for the automatic derivation of a concrete product based on a given variant configuration, a mapping between features in the problem space and their implementation in the solution space is required [13]. Several approaches (e.g., [6]) are available for establishing general traceability among all artifacts in both problem and solution space, which includes variability information in software product lines.

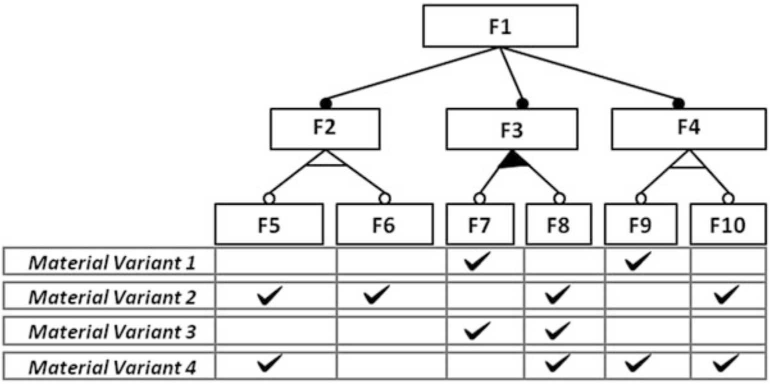

Fig. 5 Schematic representation of a mapping between problem space and solution space variability

In our approach, we use a straightforward method to establish traceability between features and variability in the hardware parts. The feature models are arranged in a way such that all their leaf nodes represent the variability of the customer-visible features (see the example in Fig. 5). All variable parts of the configurable BOM are mapped against leaves of the feature model in a matrix, where the impact of hardware parts on corresponding features is documented.

4 Configuration Activities

Configuration is the derivation of an individualized product from a component inventory such that various restrictions and dependencies are satisfied and the user requirements are fulfilled. In the context of the smart production marketplace, both the products and the factories need to be configured.

4.1 Product Configuration

The task of a conventional product configurator is to guide a customer through the derivation of a concrete product from the product family representation such that the concrete product meets their requirements [20]. Based on the product feature model, the customer is presented with a set of decisions, which are used to generate a valid combination of product features representing the desired end product.

The process of configuring a product is usually a semi-interactive procedure, where the customer selects required features from the feature tree, and the configuration tool automatically adds features that are consequences of currently selected features and disables those features for selection that would contradict some constraints. There are many extensions to standard feature models, improving their expressiveness. To mention just one, *cardinality-based feature models* allow to assign cardinalities to features, specifying the number of instances of a feature in a final configuration (e.g., a car has four wheels) [7].

The result of product configuration is an order model (cf. Fig. 1). The order consists of a 100% BOM and a 100% BOP, listing all materials and production operations necessary for manufacturing the concrete product, serving as input specification for production. These descriptions serve as input to the manufacturing execution system (MES) in the factories during physical production.

We propose to integrate within the configurator a producibility test (cf. Sect. 4.3) that checks whether the current configuration can be produced by a factory at hand. To answer this question, the configurator has to find a witness, i.e., a production workflow that shows how the product can be produced. A production workflow is a concrete, timed specification of when and which machine of the factory performs which production and transportation step.

4.2 Factory Configuration

Just like products, factories can be offered in the common marketplace, and factory models result from a configuration step. All equipment models available in the marketplace form the input to a configuration task.

A **Factory** consists of production and transportation equipment, like robots, CNC machines, or conveyors. The *topology* of the factory, not shown in the UML model in Fig. 2, is typically specified by connection associations between neighboring equipment. Materials can only be routed from one machine to another if a connection path exists in the topology of the factory. Such routing information restricts the possibilities of valid assignments of production operations to equipment. Such an equipment is a self-contained and intelligent production resource that is able to execute a defined set of production operations autonomously in cooperation with other equipment and the products to be produced. An equipment offers its production capabilities as services and can be added (plugged) or removed (unplugged) dynamically to and from the factory.

During factory configuration, the configuration service discovers the production and transportation capabilities that are offered by the equipment in the factory. Composite production capabilities between equipment based on their automation behavior, e.g., a 5D robot collaborates with a 3D-CNC machine to emulate a 5D-CNC machine, can be defined and offered as a new manufacturing service of the factory.

Factory models resulting from the configuration can be updated any time when new equipment is added or existing equipment is removed. These models serve as a basis for the product designers to decide where their products could potentially be manufactured.

4.3 Producibility Tests

Among the many services provided by the marketplace, we describe in detail one that is a backbone for many other services. We extend the task of conventional product configurators to a smart production environment, meaning that producibility must be taken into account during product configuration. The goal is to make the dependencies between products and factories transparent so that the factories can adapt themselves to changing products in the marketplace and, similarly, product designers can react to capabilities of available production facilities.

At the heart of producibility tests is a **capability matching step**, where ontology mapping [10] techniques are used to determine whether the production capabilities of a factory are enough to cover the production requirements of a product. An example is to determine whether the capability requirement description of the product in Sect. 3.3 is covered by the equipment capability description in Sect. 3.2. Inputs for a producibility test are a product model and a factory model. Producibility test (Algorithm 1: PRODTEST) consists of three major steps:

(i) *Capability matching* looks into the structure of products and factories: Production of a product is based on *production operations*, which need to be assigned to *capabilities* offered by a factory's *equipment* (cf. Fig. 2). By matching each production operation to sets of capabilities offered by the factory that are in principle able to execute this production operation, domains for the *constraint satisfaction problem* (CSP) constructed later are prepared.

(ii) *Routing constraints* are preprocessed to eliminate further invalid equipment from the domains of the production steps. This can be achieved by methods similar to *arc consistency* (or, more generally, *k-consistency*) from CSP [17].

(iii) From the remaining domains and constraints, a *constraint satisfaction (or optimization) problem* (CSP) is generated and solved to check whether the product defined by order model o can be produced by factory f. This encodes a complex decision problem comprising routing and other constraints.

Algorithm 1: Producibility test: PRODTEST algorithm

```
Data: Order Model o, and Factory Model f.
Result: True iff o is producible in f, else False.
Capability matching
Preprocess routing constraints (arc consistency)
Construct constraint optimization problem CSP
if CSP has solution then
    return True
else
    return False
```

In each of these three steps, we may recognize that the product cannot be produced by the factory currently under consideration. In this case, it may be desirable to compute recommendations how to reconfigure product or factory to make the combination producible. It may become possible for a factory to produce the product when new equipment is added to offer missing capabilities; and a product may become producible if, for example, some constraints on its specification are relaxed. Such recommendations are beyond the scope of this paper and will be addressed in future work.

Algorithms 2 and 3 answer the two queries already posed in Sect. 2.2, namely:

- **Query 1** Which factories can produce a given product?
- **Query 2** Which products can be produced by a factory?

They iterate over all known factory models/order models and call ProdTest (Algorithm 1) to determine whether the corresponding product/factory combination is feasible. This actually offers a simplistic view, because insights gained in one iteration of the loop may also be relevant in other iterations. Therefore, an algorithm combining Algorithms 2 and 3 to take the whole problem into account at once may pay off and is therefore subject of future work.

Algorithm 2: Producibility test: Query 1

Data: Order Model o, and set FM of Factory Models.
Result: Subset $prod \subseteq FM$ s.t. $f \in prod$ iff o is producible in f.
$prod \leftarrow \emptyset$
foreach *f in FM* **do** call Algorithm 1
    if *producible(o,f)* **then**
        $prod \leftarrow prod \cup \{f\}$
return *prod*

Algorithm 3: Producibility test: Query 2

Data: Factory Model f, and set OM of Order Models.
Result: Subset $prod \subseteq OM$ s.t. $o \in prod$ iff o is producible in f.
$prod \leftarrow \emptyset$
foreach *o in OM* **do** call Algorithm 1
    if *producible(o,f)* **then**
        $prod \leftarrow prod \cup \{o\}$
return *prod*

5 Evaluation of the Approach

Currently, our research is in an experimental phase. In this section, we describe our approach to self-assessment including stakeholder evaluation as part of our internal validation of the approach. To this end, we are piloting the marketplace approach in a production facility in Vienna, Austria. The purpose of this pilot study is to evaluate the overall design and to collect data for further enhancements of the approach at a conceptual level. The implementation of the local pilot enables us to identify locally relevant evaluation questions, to improve accuracy and relevance of the concepts, to empower participants, and to build capacity. Through the pilot, we aim to gather better data and better understanding of the data, to generate more appropriate recommendations, and to ensure better uptake of findings.

5.1 Marketplace Implementation

A prototype of the marketplace as described in Sect. 2 has been developed to demonstrate the feasibility of the approach. It is a web application allowing different roles to define capability ontology, equipment models, and product models. The application also allows the definition of new factories based on the configuration of available equipment, the configuration of products based on feature models, and producibility tests from the perspective of both factories and product sellers.

5.2 Example Capability Ontology

As indicated above, one of the crucial modeling challenges is the representation of capabilities and the definition of a standard vocabulary for specifying their behavior, properties, and restrictions. In our evaluation study, we have chosen an excerpt of a capability ontology based on the DIN 8593 standard [9] from the German Institute for Standardization (see Fig. 6), which shows a taxonomy of different types of *manufacturing* capabilities. Each capability in the ontology is described in detail as shown in Fig. 3. The example in Fig. 6 is only to give the reader an idea of what other capabilities are present in such an ontology.

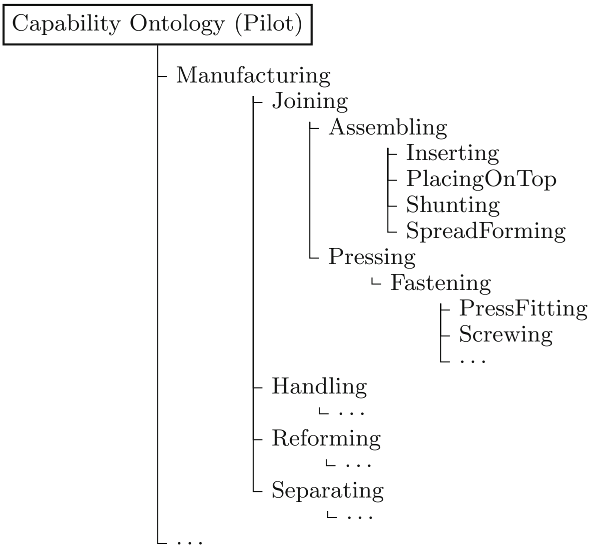

Fig. 6 Example of the capability ontology (based on the standard DIN 8593) used in the pilot setting. Each capability is described in detail as shown in Fig. 3

5.3 *Product Modeling*

For evaluation purposes, we have chosen the product to be a low-voltage power controller module called *Psupply XC*.[4] The product seller in this case is Siemens and the consumers are building businesses. The product comes in multiple variants based on customized housing (colors, labels), various qualities given capabilities of electronic parts, energy efficiency, etc.

As depicted in Fig. 7, the product consists of a printed circuit board (PCB) and its cover box, where different variants of the lid are possible. Different electronic components that can be welded to the PCB result in different features provided by the product. Variability in the hardware can be seen in the right part of Fig. 7. To the left, production operations are shown that map to individual material parts in the BOM.

The variable parts of the BOM are then mapped to the product's feature model shown in Fig. 9. Each leaf in the feature tree is associated with the hardware parts that are necessary for providing the specific feature. For example, if the feature `leakage current 0.7A` is selected, then only the hardware part `Choke1` can be selected because `Choke2` and `Choke3` do not provide this feature.

[4] *Psupply XC* is not a real product name but a pseudonym for illustrative purposes.

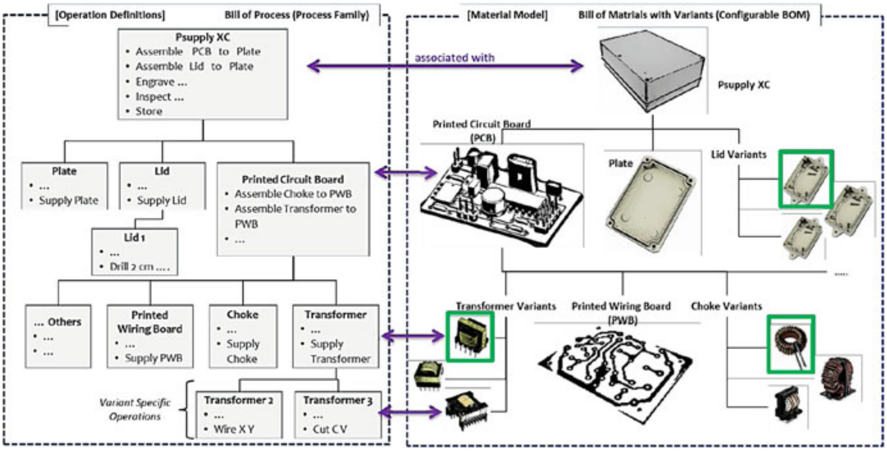

Fig. 7 Configurable BOP and BOM of the selected product in our pilot study. This is a simplified view of both BOM and BOP as the real models would cover several pages

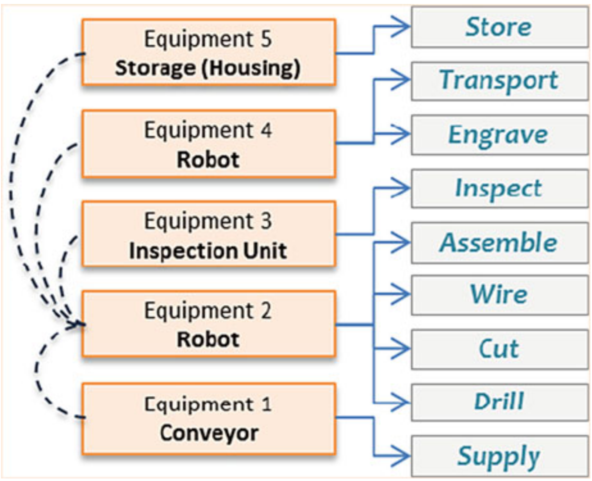

Fig. 8 Equipment topology and the capabilities of each equipment as modeled for evaluation purposes to manufacture the test product Psupply XC

5.4 *Equipment and Factory Models*

In order to demonstrate the complete cycle from product design via configuration to production, we modeled a set of factory equipment that provide the necessary manufacturing services for our selected product.

As shown in Fig. 8, we have modeled five different types of factory equipment. They provide a range of production services required by the product Psupply XC used as an example in our evaluation study. For demonstration purposes, all available equipment were selected to be part of the example factory.

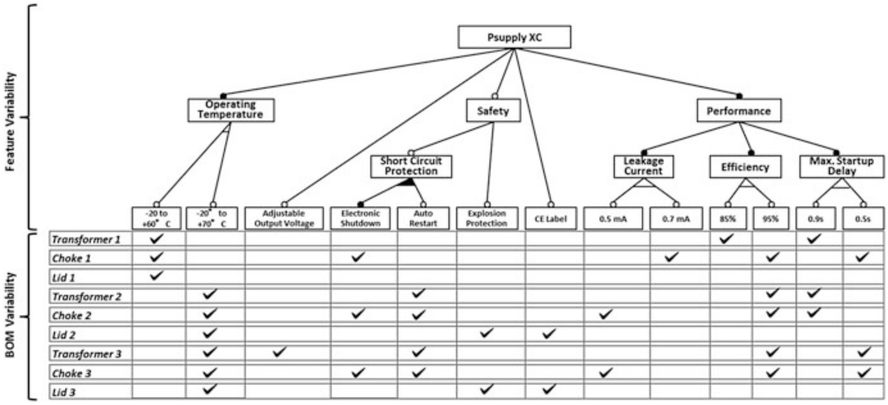

Fig. 9 Mapping between feature model at the top (problem space) and the variable parts of the configurable BOM hardware parts at the bottom (solution space)

5.5 *Product Configuration*

After the product model (excerpts in Figs. 7 and 9) is published to the marketplace, end users looking for a power supply can start a configuration process to define the features they are looking for. The system presents the feature model of the product in a nice user interface enabling users to select desired features while enjoying auto-completion and automatic filtering employing a constraint solver integrated in the back-end.

After the configuration is done, the marketplace generates the order models, trimming the configurable BOM to a manufacturing BOM automatically by removing the variant parts of the BOM based on the user selection and the mappings to the feature model (Fig. 9).

Producibility tests are run on the order models to see whether the product currently configured can be manufactured by the factories available in the marketplace. In our experimental setting, the example factory can produce the example product (as it was designed to fulfill this criterion). Nevertheless this process clearly demonstrates the workflows in the marketplace, which was the primary goal of our evaluation.

6 Related Work

Traditional product line engineering provides a lot of insights into how variability of the products must be managed, which processes must be followed in a proper product line engineering organization, etc. Apart from that, many tools for modeling products [1, 3, 23] and deriving customer-specific variants [19, 21] are already available in the market. These tools and approaches, however, do not integrate product and production modeling and do not follow the idea of an open marketplace, where product sellers and production service providers can collaborate.

The idea of a marketplace/app store as a collaboration platform for software-driven ecosystems is not new; this has been defined and discussed by the research community, e.g., [15]. Our approach can be compared to an app store in the sense that the services provided by different parties can be "bought" through this platform.

A step toward considering manufacturing during product configuration was made by Campagna and Formisano in [5], who combined product and production process modeling in their framework ProdProc. ProdProc provides constraint-based languages both for product modeling and specification of process steps for production. Coupling constraints connect these two aspects that correspond to a product's BOM and BOP. Our approach of smart production ecosystems goes a step further by taking configuration and capabilities of the factory and its production equipment into account.

Flexible and autonomous manufacturing systems play a special role in mass customization-based production models [18]. Without a transition to a flexible production environment and the integration of production engineering into product configuration, increase in product variability and customization would result in tremendous increase of production costs. Small lot sizes and high variability in a multi-product production environment require the ability of easy reconfiguration of production facilities [2]. Thomassen and Alfnes study in [22] the major challenges when adopting mass customization principles in engineering-to-order manufacturing. Bossen et al. developed a conceptual model in [4] to extend the scope of product architectures and platforms to incorporate production architectures and platforms.

Configuration of cyber-physical systems has to deal with new kinds of variability, such as the variability of topological abstractions [11] and variability of runtime capabilities. Modularity is a key principle in the *SmartFactory*^{KL} project [14], defining a modular architecture of production facilities to make it possible to produce different product instances on the same production line. For that, fast reconfiguration of the production line is necessary. Also, e.g., [24, 25] emphasize that flexibility and changeability in manufacturing are a key issue for future factories.

The idea of Manufacturing-as-a-Service (MaaS) is also gaining popularity in the context of production service management. A concept and architecture for dynamic customization of products based on production network availability presented by Yip et al. [26] is an interesting approach in this context. Similar to our approach, Yip et al. propose components for product configuration, manufacturing service management, and the integration of factory IT systems. However, the marketplace as a collaboration platform for ecosystem participants is unique in our approach.

7 Lessons Learned and Future Work

Variability in products and the resulting complexity of manufacturing processes have enforced our idea that the factory itself should be seen as a product line of manufacturing services. A common vocabulary is needed to bridge the gap between product configuration and production configuration where we propose the use of an ontology describing the production capabilities. Our research so far has shown that this common vocabulary needs to be very flexible, extensible, and reusable for a common agreement between product designers and factory operators. Standardization of such a vocabulary would be essential in the long run.

Our experience in modeling the products and factory equipment so far has shown that the data required for such modeling tasks is often available in existing PLM and PDM tools. Tool support and connectors to PLM tools are therefore a crucial part for the success of this approach. Many production tasks cannot be automated, and it is important to consider human workers involved in the production processes. We are currently working on ways to "model" human beings as an important part of the factory that also provides production services. This adds another dimension of complexity: safety of the human beings in an automated factory needs to be addressed separately. We aim to continuously improve our approach. Some of the inevitable next steps are to address the following issues.

Privacy Preserving Ecosystem Interactions: Product design specifications, factory capabilities, and details of factory components typically represent crucial intellectual property of their owners. For a smooth operation of the smart production ecosystem, all these entities must be formally modeled and shared between the stakeholders by publication to the marketplace. However, due to the crucial nature of the information, voluntary sharing of such models and information is very unlikely. New concepts and tools are required in this area (e.g., based on blockchains).

Reconfiguration Recommendations: As already mentioned in Sect. 4.3, it is not unusual that a given product cannot be produced by a given factory, in which case the producibility test fails. In this case, diagnosis and recommendation techniques may be able to suggest reconfigurations to product or factory to establish producibility. This is explored in our ongoing research. Improvements in this area may go hand in hand with improvements to Algorithms 1, 2, and 3, such as exploiting structural properties by examining the whole problem at once.

Composite Skills and Machine-Machine Collaboration: So far we have addressed production services fully offered by one equipment. However, we have been confronted with situations where one production service is the result of a collaboration between multiple factory equipment (e.g., two robots working together). Modeling such composite services and enabling them to be offered in the marketplace is part of our future work.

So far, our approach looks promising, as we have demonstrated its feasibility in pilot settings. Nevertheless, an ecosystem lives and dies with the commitment and engagement of the individual players. A marketplace is simply a "tool."

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Exploring Barriers Toward the Development of Changeable and Reconfigurable Manufacturing Systems for Mass-Customized Products: An Industrial Survey

Ann-Louise Andersen, Jesper Kranker Larsen, Kjeld Nielsen, Thomas D. Brunoe, and Christopher Ketelsen

Abstract Cyber-physical reconfigurable manufacturing systems that are able to efficiently produce customized products in lot sizes of one have the potential to significantly advance mass customization. Necessary enabling technologies are fast developing; however, the fundamental enabling principles of changeability and reconfigurability are still far from being reality in industry. Therefore, this paper explores organizational prerequisites and barriers for the development of changeability and reconfigurability, as well as significant differences regarding their presence in various industrial settings. The findings indicate that important prerequisites are only rudimentarily developed and that knowledge regarding reconfigurable system design is limited. Additionally, a long-term view on investments in production capacity and a strong coordination between production and product development were identified as prerequisites which existence are contingent on the industrial setting. The findings provide valuable insight into how to support an industrial transition toward changeability, in order to create the foundation for smart mass customization manufacturing.

Keywords Changeable manufacturing · Reconfigurable manufacturing · Mass customization · Smart factory · Industry 4.0

1 Introduction

With increasing heterogeneity of markets, decreasing product life cycles, and rapidly emerging new product features and materials [1], the development and implementation of industrial cyber-physical reconfigurable systems appears

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promising in terms of greater resource efficiency, shorter time to market, higher value products, new business models, and affordable product customization [2]. Essentially, these cyber-physical systems that merge the physical and digital world and vertically integrate the factory capture the essence of the fourth industrial revolution and mass customization manufacturing, enabled by (1) interoperability of system modules, machines, devices, sensors, and people; (2) transparency of information, e.g., virtual twins, real-time data on operations, or information related to suppliers or customers; and (3) autonomy in, e.g., system reconfiguration, scheduling, failure recovery, or performance improvements [3–5]. Factories of the future are expected to have these features, being reconfigurable, autonomous, and self-adapting; however, they are still far from being reality in industry [6]. Organizational and change management-related aspects of this remain challenging, e.g., integrating new technologies with existing systems, simultaneous consideration of production and products, identification of suitable application fields, and adjustments of organizational structures [3, 7]. On the contrary, the technological aspects of these systems are either present or advancing very quickly, e.g., wireless sensor networks, big data, and cloud computing [5, 7]. Therefore, well-designed manufacturing systems that have fundamental features of changeability and reconfigurability, e.g., modularity in both physical and logical design features, plug-and-play machines and controllers, and reliable flexibility for anticipated functional requirements, have been emphasized as being likely to evolve into smart and networked manufacturing systems with high degrees of autonomy [5, 6].

Thus, the vision of cyber-physical, autonomous, and reconfigurable manufacturing systems being self-adapting and self-organizing can be viewed as an extension of the reconfigurable manufacturing system (RMS) concept proposed in the late 1990s, providing increased levels of manufacturing flexibility, product customization, and lot sizes of one [8, 9]. Yet, the successful realization and development of manufacturing systems that possess the fundamental characteristics of changeability and reconfigurability appears to require a paradigm shift in industry, as dedicated, rigid, and static systems are traditionally designed and operated [10–12]. At present, research on changeability and reconfigurability focuses widely on technical dimensions, e.g., reconfigurable tools [13], reconfigurable controllers [14], and reconfigurable machines [15], whereas limited research addresses organizational and management-related prerequisites and barriers in the path to realization of the benefits of changeability and reconfigurability [16] and eventually cyber-physical systems [7]. Furthermore, significant differences in the readiness and qualifications of different industries and company types are expected toward the realization of changeability and reconfigurability as a foundation for future smart systems, e.g., between large and small enterprises [17] or industries with different degrees of required product innovation and customization [3]. Consequently, a viable first step toward realizing an evolutionary path toward cyber-physical, autonomous, and reconfigurable systems that enable high levels of affordable customization and personalization is to support the industrial development of fundamental changeability and reconfigurability characteristics, considering important differences across industrial settings, by focusing on organizational and change management-related aspects rather than solely addressing technical aspects. This leads to the following research question: What are critical barriers in industry toward the development and realization of changeable and reconfigurable manufacturing systems, and can significant differences regarding their presence in different manufacturing settings be identified?

2 Related Research

Changeable manufacturing is widely acknowledged as the manufacturing paradigm of the future, defined as manufacturing systems that respond to change on all levels in an economically feasible way [18]. Changeability can be realized through various physical and logical enablers embedded in the manufacturing system, e.g., scalability, convertibility, mobility, modularity, etc. [11]. Reconfigurable manufacturing systems that provide capacity and functionality as needed through modularity, integrability, convertibility, customization of flexibility, and scalability enable changeability on system, cell, and workstation level [12].

The technical features of the changeable and reconfigurable manufacturing system differ from traditional manufacturing systems, being either dedicated for a few products or designed for preplanned flexibility [11]. Technical barriers related to this are widely emphasized and addressed in previous research, e.g., developing the control system, controlling process variation, establishing interfaces, developing appropriate tooling, etc. [16]. However, the design and development of changeable and reconfigurable manufacturing has in research been emphasized as challenging in numerous ways, going well beyond technical dimensions. Likewise, regarding a production system purely as a technical system neglects critical social, human, and organizational dimensions, as system design is a "double-task" covering both planning and conducting the design process and the actual design itself [19]. Thus the ability to create an organizational foundation and process for actually designing changeability and reconfigurability should be considered as well, which is dependent on company culture, traditions, readiness to change, way of working, etc. [20, 21].

As changeability is a life-cycle and nonfunctional property in a manufacturing system that can be realized in various ways and manifests itself after the system has been put into use [22, 23], its design is more complex than in cases of traditional manufacturing systems [24]. In previous research, the following fundamental elements of design for changeability and reconfigurability have been emphasized: (1) anticipation of requirements of scalability and convertibility throughout the system's lifetime, (2) conceptual and detailed design of a system with the right degree and enablers of changeability, and (3) continuous selection of configurations and changes in the systems' operating time closely integrated with product development [24]. As these design tasks advance the design and development process, additional organizational capabilities are necessary prerequisites for success. However, this has only received limited attention in previous research. Malhotra et al. [16] evaluate

Table 1 Design prerequisites for changeability and reconfigurability [27]

Prerequisites
A life-cycle perspective on production systems [25]
Coordination between production system design and the product portfolio development [25]
Having long-term view on investments in production capacity [26]
Having a structured production system design process [26]
Having a holistic perspective on production systems [26]
Having staff that is skilled in system design and have knowledge of reconfigurability [26]
Existence of product families for customized flexibility in production [26]

numerous barriers related to the successful implementation of reconfigurability, however, primarily being of technical nature. Rösiö and Jackson [25] address important preconditions for designing changeable manufacturing, having a life-cycle perspective on production systems and correlating product and production design. Likewise, Rösiö [26] emphasizes certain organization-related preconditions that should be considered prior to design of reconfigurability, e.g., applying a long-term view of the system, the ability to integrate the system design with the product portfolio, staff skill and knowledge of reconfigurability, a structured system design process, and readiness to have life-cycle perspective in production and investments. Andersen et al. [27] summarize these prerequisites for development of changeability, recited in Table 1, and conduct a case study for examining their presence and potential actions that will lead to these. The work presented in this paper is built on the premise that if the various factors identified as preconditions for successful development of reconfigurability are not present in a manufacturing company, this should be regarded as a critical barrier in the transition toward changeability and reconfigurability. Their findings indicate that the investigated prerequisites are not largely present and that various challenges exist in this regard [27]. However, there is still limited generalizable empirical evidence going beyond case studies, regarding the presence of these prerequisites, as well as potential industrial differences in the readiness toward development of changeability and reconfigurability.

3 Research Method

In order to address the research question stated in Sect. 1, a questionnaire survey has been conducted. The empirical inquiry is primarily descriptive and exploratory, aiming at determining critical barriers toward the realization of changeability and reconfigurability and exploring any significant differences across different industrial settings. Thus, a larger sample representing various industrial settings is required, in order to provide more generalizable empirical evidence, which is the reason why the survey method has been selected as the appropriate research method [28, 29].

3.1 Questionnaire Design

Based on the prerequisites presented in Table 1, which have been identified as critical preconditions for development of changeable and reconfigurable manufacturing in previous research, a questionnaire survey has been developed. The questionnaire survey was designed in two sections to reflect the unit of analysis being the manufacturing company: (1) background questions on the company, the products, and the production setting and (2) questions regarding barriers toward development of changeability and reconfigurability. The questionnaire was developed and published in both an English and a Danish version in SurveyXact [30].

In the first part of the survey, essential characteristics of the manufacturing firm were addressed, e.g., organization size and the country and industry in which the organization operates; the type of products offered, e.g., degree of variety and customization; and the type of production being utilized, e.g., degree of automation, the annual production volume, and the extent to which different production policies are utilized. For the second part of the questionnaire, all prerequisites in Table 1, representing the latent variables, were operationalized as readily understandable statements that could be assigned numerical values. A five-point ordinal Likert scale was used (1 = strongly disagree, 2 = disagree, 3 = neither disagree or agree, 4 = agree, 5 = strongly agree). Respondents were also given the possibilities to indicate uncertainty about each question. In Table 2, the latent and measured variables of the survey are presented.

Table 2 Latent and measured variables of the questionnaire survey

Latent variable	Measured variable	Variable ID
A life-cycle perspective on production systems Having a holistic perspective on production systems	We are focused on reusing production lines and equipment across the product program or for new generations	PRE1
Coordination between production system design and the product portfolio development	In our development activities, there is strong coordination between production system development and product portfolio development	PRE2
Having long-term view on investments in production capacity	We apply a long-term view on investments in production capacity	PRE3
Having a structured production system design process	We apply a structured and well-documented production system design process	PRE4
Having staff that is skilled in system design and have knowledge of reconfigurability	We have sufficient knowledge on how to develop reconfigurable production	PRE5
Existence of product families for customized flexibility in production	Families of products and parts can be identified within our product program based on various similarities	PRE6

3.2 Data Collection and Respondents

Prior to publishing the questionnaire survey and starting the data collection, the questionnaire was pretested in a closed forum of experts from academia, in order to test the appropriateness of questions, terminology, and questionnaire format. Less than 5% of minor changes were made in terminology and in questionnaire setup. Hereafter, the questionnaire was emailed to an initial target group of 128 individuals representing different manufacturing companies, which were selected based on a qualitative screening of suitable potential respondents in each authors' network of connections in manufacturing companies. The individuals were targeted only if their positions in the manufacturing companies appeared to represent both detailed knowledge on product and production development activities and general knowledge about the company and its activities. Thus, the initial target group covered production specialists and engineers, operations managers, plant superiors, as well as other types of managers with production-related responsibility.

From the initial target group of respondents, 39 full responses resulted. In order to increase this response rate, follow-up mails and phone interviews were conducted. Furthermore, the questionnaire was distributed in a newsletter for Danish manufacturing companies to increase the sample size. In doing this, the sample was increased to 60 full responses. In Fig. 1, the distribution of responding companies is categorized by their size, industry, country, and annual sales volume.

In addition, as part of the background information on the responding companies, the following characteristics were indicated: the percentage of production processes that are manual, semiautomated, and fully automated, the percentage of products that are customized or more standard offerings, and the percentage of production being make-to-stock, assemble-to-order, make-to-order, or engineer-to-order. The distribution of the sample across these characteristics is presented in Table 3.

The responding companies were primarily located in Denmark, and half of the responding companies are characterized as being small- and medium-sized companies (SMEs), whereas 40% represents large enterprises. The degree of full automation of production is generally low in the sample, whereas high degrees of manual work are more dominant. Some degree of product customization is generally present in the investigated companies, and there is a low degree of production of purely standard products.

3.3 Data Analysis

The data analysis was conducted using the statistical software IBM Statistical Package for the Social Sciences (SPSS) version 24. Firstly, the collected data was thoroughly examined and reviewed, where "uncertain" responses were recoded as discrete missing values and blank responses were removed. In order to evaluate the internal data reliability, the Cronbach alpha test was used with a cutoff value of

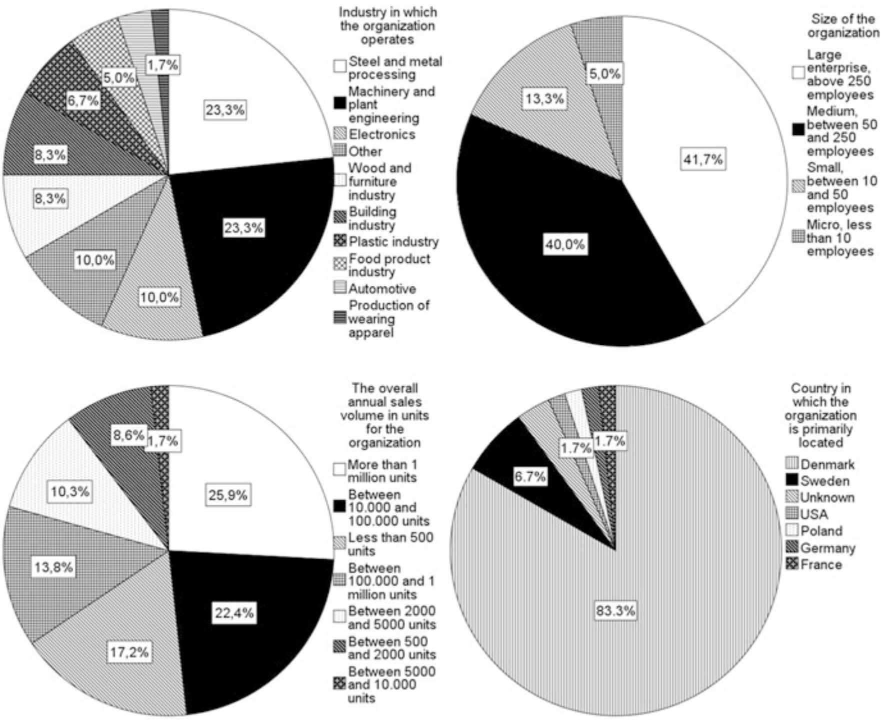

Fig. 1 Industry, size, sales volume, and country characteristics of sample

Table 3 Product and production characteristics of sample

Distribution of responses regarding percentage of production that is automated						
	0%	*1–25%*	*25–50%*	*50–75%*	*75–99%*	*100%*
Manual work	2%	22%	22%	24%	27%	3%
Semiautomated	5%	59%	20%	10%	5%	0%
Fully automated	30%	47%	18%	2%	4%	0%
Distribution of responses regarding percentage of product types						
	0%	*1–25%*	*25–50%*	*50–75%*	*75–99%*	*100%*
Custom-ordered products	9%	43%	12%	7%	14%	16%
Standard products with variants	16%	24%	21%	12%	22%	5%
Standard products without variants	45%	29%	7%	14%	2%	3%
Distribution of responses regarding percentage of production policies						
	0%	*1–25%*	*25–50%*	*50–75%*	*75–99%*	*100%*
Make-to-stock (MTS)	38%	36%	13%	9%	4%	2%
Assemble-to-order (ATO)	50%	20%	13%	5%	11%	2%
Make-to-order (MTO)	5%	29%	13%	11%	25%	16%
Engineer-to-order (ETO)	43%	41%	5%	7%	4%	0%

$C\alpha \geq 0.7$ as suggested by Kline [31]. Therefore, as the measured variables have a combined Cronbach alpha value of 0.831, the consistency of the data is considered adequate. Furthermore in order to assess the normality of the data, the Kolmogorov-Smirnov test and Shapiro-Wilk test were applied. All data appeared non-normally distributed for both the Kolmogorov-Smirnov test $p \leq 0.05$ and Shapiro-Wilk test $p \leq 0.05$; therefore, nonparametric statistics were selected for subsequent data analysis. The aim of the data analysis is twofold. First of all, the most critical barriers toward development of changeability and reconfigurability have to be identified, represented by the prerequisites that in the survey were indicated as having the lowest degree of presence. The relative importance index (RII) in Eq. 1 was applied for this in order to rank each prerequisite from 0.0 to 1.0, as used previously by Larsen et al. [32] and Lindhard et al. [33]. In Eq. 1, W_i is the total sum of each measured variables' assigned values; A is the highest weight in this research, being five; and lastly N is the total number of respondents for each measured variable.

$$\text{RII} = \frac{\sum_{i=1}^{5} W_i}{A \times N} \tag{1}$$

Secondly, significant differences in the presence of prerequisites across different industrial settings were explored, by applying the Kruskal-Wallis test for significant differences between measured variables and group variables. The grouping variables represent background variables indicated in the survey, as described in Sect. 3.2. As the data were well above the minimum sample size, 22 respondents with $\alpha = 0.05$ [34], the asymptotic method optimized with Monte Carlo (10.000 simulations) was applied. Lastly, post hoc tests were conducted using the Mann-Whitney test and Bonferroni correction, in order to ensure that type I errors did not work up more than 0.05.

4 Survey Results

In Table 4, a ranking of the investigated prerequisites for development of changeable and reconfigurable manufacturing is presented, based on the survey results and the RII calculations. The prerequisite with the highest rank (PRE1) represents the most implemented prerequisite, having the highest value of agreement with the statements presented in the questionnaire and thus the highest RII.

In Table 5, the results of the Kruskal-Wallis test are presented. The tested null hypothesis, being no significant differences between respondent's background information and the degree of presence of the prerequisite, was rejected in three cases, if considering both the asymptotic and the Monte Carlo results.

In Table 6, the results of the Mann-Whitney test are presented. In addition, Fig. 2 depicts box plots for the combinations of measured variables and the groups of respondents appearing to be significantly different. In the plots, some outliers are

Table 4 Relative importance index (RII) and ranking of measured variables

Measured variable	Variable ID	*n*	RII	Ranking
We are focused on reusing production lines and equipment across the product program or for new generations	PRE1	59	0.78	6
In our development activities, there is strong coordination between production system development and product portfolio development	PRE2	57	0.66	3
We apply a long-term view on investments in production capacity	PRE3	58	0.71	4
We apply a structured and well-documented production system design process	PRE4	57	0.63	2
We have sufficient knowledge on how to develop reconfigurable production	PRE5	57	0.61	1
Families of products and parts can be identified within our product program based on various similarities	PRE6	58	0.76	5

Table 5 Kruskal-Wallis tests for significant differences between background variables and measured variables

Grouping variable (independent)	Measured variable (dependent)	*n*	x^2	Assump. sig.	Monte Carlo sig.
Industry in which the company operates	PRE2	57	16.374	0.059	0.034
Percentage manual processes	PRE3	57	8.765	0.033	0.028
Percentage of semiautomated processes	PRE3	57	6.244	0.012	0.013

present for groups of background variables; however, as the data tests are based on an indexed ranking of the data and not the absolute values, outliers have not been removed.

5 Discussion

The results of the survey indicate that the investigated prerequisites for developing changeable and reconfigurable manufacturing generally are only rudimentary existing in the responding manufacturing companies. In fact, an average RII across all six prerequisites (0.69) does not indicate a general agreement about the enablers being present in the companies. Thus, it appears that the investigated companies still lack fundamental organizational capabilities in terms of developing and realizing manufacturing changeability and reconfigurability, being critical enablers for efficient mass customization. The least present prerequisites appeared to be knowledge and skills of employees regarding reconfigurable manufacturing system design and the application of a structured and well-documented system design process. These findings are in line with previous, however sparse, research

Table 6 Mann-Whitney tests for grouping variable combinations. The significant level for industry is 0.005 for both group combinations, for degree of manual processes is 0.008, and for degree of semiautomated is 0.012

Grouping variable (independent)	Measured variable (dependent)	Variable combination	*n*	x^2	Assump. sig.	Monte Carlo sig.	Z-value	Effect size
Industry in which the company operates	PRE2	Machinery and plant engineering – electronics	18		0.005	0.006	−2.779	−0.154
Industry in which the company operates	PRE2	Steel and metal processing – food product industry	17		0.009	0.005	−2.628	−0.155
Percentage manual processes	PRE3	50–75% – >75%	31		0.009	0.008	−2.608	−0.0841
Percentage of semiautomated processes	PRE3	<25% – >25%	57		0.012	0.013	−2.499	−0.0438

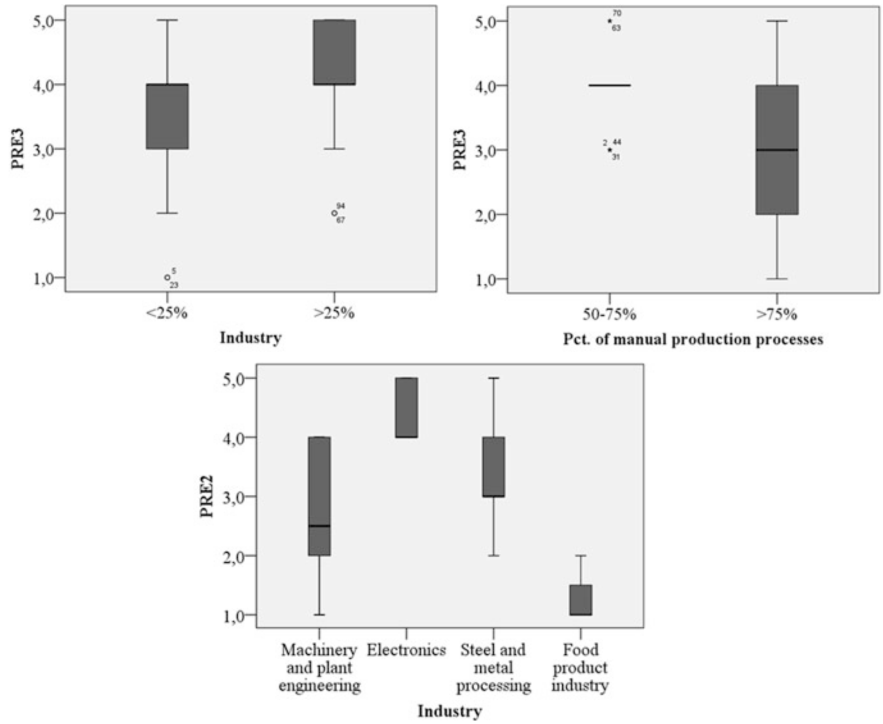

Fig. 2 Box plots of measured variables and group combinations appearing significantly different in the Mann-Whitney test

on the topic, stating that the design and development of manufacturing in general tend to be rather ad hoc and less systematic or well-documented [20, 35] and that industrial knowledge and consideration of reconfigurability and design of reconfigurable manufacturing remains limited [35, 36], e.g., in terms of types of changeability, reconfigurability, and flexibility and lack of design methodologies for changeability that are readily applicable in industry [14, 24, 26]. This can be argued as representing a major barrier toward the development and implementation of changeability and reconfigurability in industry, as changeability increases the complexity of the design process and requires initial thorough consideration of requirements, e.g., functionality and capacity changes and corresponding suitable enablers [24, 25, 35]. Thus, design for changeability cannot be sufficiently supported by unstructured or traditional approaches to production development, which appears present in the investigated companies. On the contrary, the most present prerequisite was in the survey indicated as being focused on reusing production lines and equipment for multiple products and new product generations, which represents a complete life-cycle or holistic view on production. Likewise, the survey findings suggest that the existence of product or part families for customized flexibility is one of the most present prerequisites in industry. These findings support previous case-study findings by Rösiö and Säfsten [35], indicating that customization of production flexibility is considered to higher extent in production system design than other characteristics of reconfigurability. However, in order to successfully design and develop changeable manufacturing systems, support for determining the right degree and type of changeability remains treated only to a limited extent in research [24].

The presence of the various prerequisites was found to be contingent on the manufacturing setting, as both the industry in which the firm operates and the degree of automation were indicated as background characteristics with significant differences in prerequisite presence among group combinations. First of all, the correlation between production system design and the product portfolio development appeared more present in companies within the electronics industry than in the machinery and plant engineering industry. A strong coordination between products and production is important when designing for changeability, as the process and technology platform should be continuously matched with the product and its features, in order to efficiently provide flexibility and capacity as needed and reuse rather than replace equipment [11, 25]. Evidently, the criticality of this increase with the rapidness of new product introduction and decreasing product life cycles is a considerably dominant characteristics of the electronics industry. Likewise, this strong simultaneous consideration of product and production development appeared more present in the steel and metal processing industry than in the food processing industry. A possible reason for this can be found in the consideration and implementation of mass customization and personalization in the food industry, which is developing, but far from common practice [37, 38]. Thus, in the food processing industry, the need for rapid change of production processes and technologies in accordance with product changes is less dominant, due to reliance on established processes, large batches, and no product customization [37]. Nevertheless, the potentials in future customization of nutrition and food products are promising, which indicates that changeability and reconfigurability are viable options in this type of industry that requires further research.

The second prerequisite which was found significantly different in terms of presence in different industrial settings is the existence of a long-term view on investments in production capacity, which appeared less present in companies with highest degrees of manual work, as well as less present in companies with low levels of semiautomated production processes. Having a long-term view on investment in production capacity is fundamental in terms of enabling physical capacity scalability and reusing capacity across the product portfolio, e.g., products in mature, declining, or introductory phases. Evidently, hard scaling of capacity is required to higher extent in settings with a high level of automation, whereas logical scaling of capacity in terms of workforce and working hour changes is required in settings with a high degree of manual work [11, 39]. Thus, the findings of the survey support this and indicate that enablers of changeability, e.g., scalability, convertibility, etc. [18], which can be differentiated based on physical and logical appearance [18], are not widely applicable in all industrial settings, however, being treated only to a limited extent in design methodologies for changeability and reconfigurability [24, 40].

In order to extend the findings reported in this paper, further generalization beyond Danish industry is required, which is dominant in this survey. It is expected that the readiness and degree of implementation of changeability, reconfigurability, and smart factories may be higher in some industries, which are not highly represented in this survey, e.g., the automotive industry. Increasing the sample size to covering more responding companies from this type of industry will likely lead to different conclusions than reported here. However, as previous research on changeability and reconfigurability tend to focus particularly on the automotive industry [22, 35, 41, 42] or the electronic industry [10, 43], the importance of covering other industrial settings and providing wider and generalizable empirical evidence should be emphasized.

6 Conclusion

In this paper, prerequisites and barriers for the development of changeable and reconfigurable manufacturing were investigated, as an important organizational foundation for further transitioning toward smart factories and cyber-physical reconfigurable manufacturing systems that enable new levels of efficient product customization and personalization. An industrial survey was conducted, in order to explore the presence of critical prerequisites for development of changeability and reconfigurability and their contingency on the type of industrial setting. The collected survey data cover primarily Danish companies, however, representing both large enterprises and SMEs in a wide range of different industries. The main findings are:

- The different prerequisites are in general only rudimentary existing in the responding companies, and the least existing prerequisites are knowledge and skills regarding reconfigurable system design and the application of a structured and well-documented system design process. This should be considered as major barriers toward an industry transition toward manufacturing systems enabling affordable customization, variety, rapid product introduction, and small lot sizes.
- The presence of prerequisites of changeability and reconfigurability is contingent on the industry in which the firm operates and the degree of automation utilized in production.
- Correlation between production system design and the product portfolio development was more present in companies within the electronics industry than in the machinery and plant engineering industry, as well as more present in the steel and metal processing industry than in the food processing industry.
- Having a long-term view on investment in production capacity, which is fundamental in terms of enabling capacity scalability and reuse across the product portfolio, appeared less present in companies with highest degrees of manual work, as well as less present in companies with low levels of semiautomated production processes.

The findings indicate that changeability and reconfigurability are not universal capabilities being equally important in all types of manufacturing settings, as the objective, e.g., being able to physically scale production capacity, appears to differ. Consequently, further research on changeability and reconfigurability should focus on capturing significant differences in application and enablers across industrial companies, in order to sufficiently support an industrial transition. Furthermore, focus should not only be on the fast-evolving technical features of cyber-physical reconfigurable manufacturing systems but also organizational and management aspects related to transitioning from traditional and more dedicated factories to the smart and highly changeable factories that capture the essence of Industry 4.0 and realize mass customization.

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3D Avatar Platforms: Tomorrow's Gateways for Digitized Persons into Virtual Worlds

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Abstract 3D avatar platforms are tools for offering customer services for production, distribution, and consumption of 3D avatars as a product. In this way 3D avatar platforms will become essentially a virtual home for realistic 3D avatars that can be used to explore virtual worlds that are a part of the platform or can be used as a "vehicle" for visiting virtual worlds on different platforms. Research on existing 3D avatar platforms is described in the paper, alongside their capabilities, tools, and the virtual worlds they offer. A 3D avatar platform showcase was developed for CeBIT 2017 as a proof of concept, and it will be used in the future as a gateway for digitizing persons into virtual worlds. The paper conceptualizes the possibilities and features of future 3D avatar platforms.

Keywords Human 3D scanning · Web platforms · 3D content · 3D avatars

1 Introduction

An avatar is a graphical representation of a person. It can be three- or two-dimensional. An avatar can be a realistic, fateful, representation of the person in question, a cartoonish look-alike, or even an entirely fantastic representation that looks nothing like the person behind it. Avatars can be produced using various 3D full-body scanning technologies, using photographs, and/or using 3D/2D modeling and graphical software tools. The avatar continuum varies from the simplest static

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representation to fully articulated (dynamic) avatar that can be controlled by a person in real time or by AI [1]. The term "3D avatar," if not otherwise indicated, is used in the paper to represent a dynamic, articulated, 3D avatar. The main focuses of the paper are 3D avatars that are realistic representations of a person and web platforms that cover all three parts of 3D avatar life cycle: production, distribution, and consumption. The 3D avatar production phase covers all the processes needed to produce an articulated realistic 3D avatar. The distribution phase covers services for distribution of 3D avatars to the customers. The consumption phase includes software tools, 3D applications, and various contexts in which produced 3D avatars are exploited and used.

3D avatars are widely used, and their utilization is constantly growing as they are appealing and beneficial on many levels [2, 3]. From a simple personal curiosity regarding one's own 3D representation especially in virtual worlds, through everyday leisure activities such as entertainment or shopping, to the very beneficial such as fitness or health [4]. The use of 3D avatars in entertainment, social interaction, or even learning is nothing new but was long dominated by generic avatars (modeled by an artist or created procedurally through an implementation of an algorithm) that in the best cases it only resembled the persons they represented, and in most cases they were inaccurate representations be they abstract, fantastical, or merely inaccurate.

Technologies for producing realistic 3D avatars are becoming more and more available and affordable, and so the need for realistic 3D avatars is increasing. Already there are several developed technologies that provide full human body scanning and the production of a realistic digitized 3D representation. Consequently, there are companies of various sizes that provide scanning services to customers. Usually, production and distribution are integrated into one system, and the same company provides both. There are, however, situations where this service is provided by B2B partnerships wherein one company produces content while the other is in control of content distribution such as [5].

Providing all of these parts as a single customer service represents the next logical step in the 3D avatar business. Customers expect to receive their avatars in the easiest possible way and to have them available on all of their devices. Further, when they do receive their avatars, the question of what can be done with them arises. The amount of available content making use of realistic 3D avatars is constantly increasing, and it is going to increase even more with time. Already partnerships are being established between companies providing scanning services and companies providing content which makes use of the resulting avatars such as virtual worlds. One such example is partnership between Doob Group AG [6] and High Fidelity [7]. Doob Group AG is a German company providing full body scanning services with offices in Europe, the USA, Asia, and Australia. High Fidelity is a US company that provides a next-generation social virtual reality platform. This type of partnership shows both the possibility of and the need for creating a comprehensive 3D avatar platform.

3D avatar platforms are tools for providing customers with all three parts of 3D avatar life cycle as a single service. Not only can the customer order their realistic 3D avatar and receive it, but the customer will also be provided with integrated tools and content suitable for that same avatar. In this wise 3D avatar platforms will become essentially a virtual home for customers' 3D avatars that can be used to explore virtual worlds on the platform itself or as a "vehicle" for visiting virtual worlds on different platforms. In this paper all parts of a 3D avatar platform will be explored. This paper is a continuation of the previous work on describing technologies involved in human scanning and avatar production [4, 8].

The structure of the paper is as follows. In Sect. 2 research on existing 3D avatar platforms is described regardless of what part of realistic 3D avatar life cycle they are implementing. An avatar platform developed by authors for CeBIT 2017 as a proof of concept is described in Sect. 3. This platform is capable of being used in the future as a gateway for digitized persons into virtual worlds, and it is planned that it will be used for that purpose. In Sect. 4 the concept of a full 3D avatar platform covering all three parts of realistic 3D avatar life cycle is explored and described. Sect. 5 concludes the paper.

2 Background

A simple architecture of a 3D avatar platform (whose building blocks correspond to the parts of the realistic 3D avatar lifecycle) is presented in Fig. 1. There are many examples of commercial systems implementing some of the parts described in Fig. 1 and companies providing corresponding services. However, to the best of authors' knowledge, there are not many systems, aside from their own work, that provide complete coverage of the realistic 3D avatar life cycle. Also, it is not the goal of this section to present a thorough and complete description of every system that is related to the avatar business, but rather to present an overview of systems that cover services that should be included in a comprehensive 3D avatar platform. These are systems that are the most eminent and that were actual inspiration for building an avatar platform.

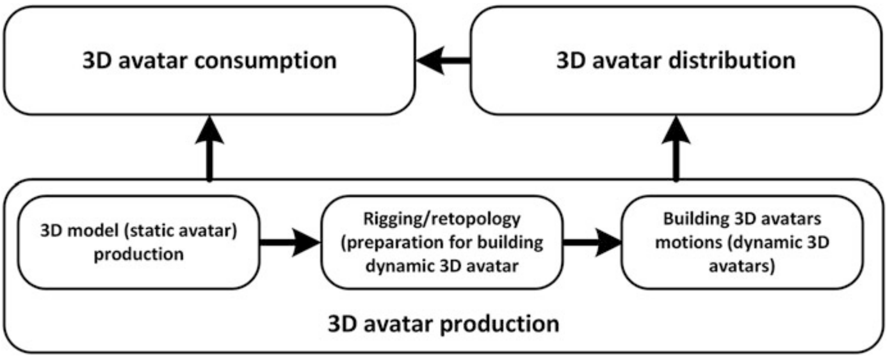

Fig. 1 A simple architecture of 3D avatar platform

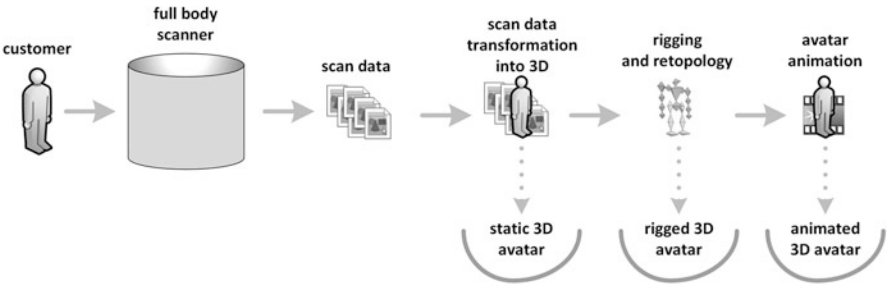

Fig. 2 Steps in realistic 3D avatar production and produced results

The production of realistic 3D avatars is not simple and consists of several steps, Fig. 2. The first step is the production of an accurate 3D model of a person's appearance. This is the static 3D avatar. It is possible to produce a 3D model of a person using modeling tools such as iClone [9], MakeHuman [10], Marvelous Designer [11], or more general tools such as Maya, 3D Studio Max, and ZBrush [12], but a lot of skill and time is required to achieve an accurate representation of a person. It is too expensive to make it feasible for the mass market and the common consumer [13].

3D scanning techniques are used to acquire data from which 3D model will be produced. There are many techniques for full human body scanning [8] such as laser triangulation scanning, structured-light scanning, time-of-flight scanning, multi-view photogrammetry systems, MRI, etc. Scanning data are used to produce an accurate 3D model of a person's appearance. This is achieved either automatically or semiautomatically, but either way in a much shorter time and with far less expense then when the model is created by a character artist/animator. Unlike 3D models produced with 3D modeling tools, the results of 3D scanning are completely fateful representations of persons scanned. The correspondence is akin to that between paintings and photographs, with the 3D scan-derived model taking the place of the photograph.

The 3D avatar platform proof of concept described in this paper is based on a multi-view photogrammetry system [14]. The principle behind photogrammetry is to take multiple images of the same object (the more overlap between images, the better the result) and then automatically register common points in each image. The position of the points in 3D space is then calculated, and the point cloud is refined and built. The 3D model and its texture are produced from the point cloud and the scanned images. More images of a higher resolution usually lead to denser point clouds and sharper textures with more detail. This all adds to the accuracy of the person's 3D representation. A typical photogrammetry scanner setup similar to the one used in CeBIT 2017 is shown in Fig. 3.

The next step after the creation of a 3D model is preparing the model for animation. For a person to be able to control the 3D avatar, proper animations of avatar actions have to exist. 3D avatars are usually animated using skeletal animation techniques [15]. When using this technique, the avatar is represented by its surface

Fig. 3 Doob Group AG's photogrammetry scanner – DOOBLICATOR 2.0 (Image courtesy of Doob Group AG)

(static 3D model) and a hierarchical set of interconnected bones (called the skeleton or rig). The process of fitting skeleton inside a static 3D model is called rigging. In addition to rigging, skinning is also applied. Skinning defines how the input motion deforms the surface of the static 3D model. Sometimes, if necessary, additional processing of the static 3D model is needed to achieve more natural movement. One example of such post-processing steps is re-topology [16] where the generated static representation of the model is reconfigured so as to describe the same surface but with polygons better suited to animation. These steps can be achieved manually, semiautomatically, or automatically. The result, from an aesthetic perspective, is achieved by manual processing using tools such as Autodesk Maya, 3D Studio Max, or ZBrush. However, very good competitive results are achievable using semiautomatic tools such as Adobe Mixamo [17] which also supports character modeling. Automatic rigging/skinning and re-topology are still in development, but even the preliminary results are promising [15].

Also, for character rigging to work (especially in automatic and semiautomatic rigging), it is necessary that the 3D model should come in a certain predefined pose. The A-pose and the T-pose are commonly used (Fig. 4). This also means that customers cannot be scanned in any kind of pose but in one of the predefined poses. From the perspective of space efficiency (how much space a customer and consequently the scanner chamber take up), the A-pose is considered better than the T-pose. From the perspective of animators, the T-pose is better as it simplifies rigging and skinning.

The last step in 3D avatar creation would include the animation of all of the avatar's actions. The 3D avatar is animated through complex manipulations of the avatar's skeleton. 3D avatar animation are produced manually, semiautomatically,

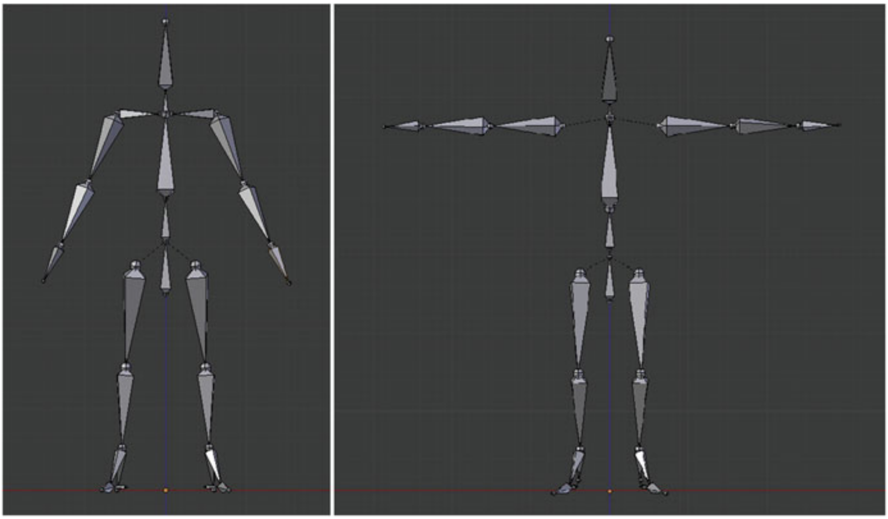

Fig. 4 A-pose and T-pose examples

or automatically using the same software tools that are used for 3D avatar rigging [16] or using complex motion capture tools such as Blade for VFX | Vicon [18]. This part of avatar production depends strongly on the avatar consumption part of the platform. Meaning, if someone wants to integrate their avatar into a computer game, the 3D avatar has to support all the actions and “moves” required from a character inside that game.

All three parts of 3D avatar production can be integrated into one service, but commonly, they are divided. For example, Shapify [19] supports a full human body scanning system and supports the 3D printing of a person’s figurine and also supports the purchase of person’s static 3D model. However, they do not support the next steps of avatar production. On the other hand, Mixamo supports automatic 3D model rigging and a plethora of predefined character animations that can be applied onto the resulting rig, but they do not offer the production of realistic 3D avatars.

The distribution part of an avatar platform implies a web shop that enables customers to purchase different aspects of their 3D avatar, or, eventually, somebody else’s avatar. At the moment there are systems that enable customer to purchase or download free of charge different static and dynamic 3D models including pre-created character animations such as Free3D [20] and CGTrader [21]. Also, there are social platforms for creation, presentation, and sharing of 3D content such as Sketchfab [22]. Full body scanning company Ten24 [23] offers various static 3D avatars for purchase and download [24]. It should be noted that customers are not purchasing just their own avatars, but also avatars of other persons. Full body scanning company IIID.me [25] offers various figurines of customer’s avatar for purchase. IIID.me is also preparing different avatar services for their customer in the future such as virtual dressing, rigging, and game export.

There is a staggering amount of content for 3D avatars in general, and every day a new content is specifically devised and created for realistic 3D avatars. Realistic 3D avatars in general [4] can be used in medicine, fitness, education, fashion, entertainment, etc. Beside these classic examples of avatar use, there are platforms and services that provide virtual worlds users can dive into with their realistic 3D avatars. Examples of these platforms are High Fidelity, Second Life [26, 27], and Blue Mars [28]. High Fidelity also offers users to create their own virtual worlds, to invite and share them with the other users.

3 CeBIT 2017 Avatar Platform Showcase

CeBIT 2017 (Doob) avatar platform is the result of cooperation between Doob Group AG and Vodafone for CeBIT 2017. It is a showcase of 3D avatar platform potentials and part of Vodafone's Smart Cities: GigaCity initiative, cloud, and hosting [29]. The platform implements the production and distribution part of 3D avatar life cycle with intention of extending the platform to cover the consumption part in the future. It demonstrates Doob Group AG's capability of providing services in full body scanning, automatic 2D to 3D data conversion, and automatic production of articulated 3D avatars.

The architecture of Doob avatar platform is described in Fig. 5. Central to the entire platform is data system which handles data storage, processing, and

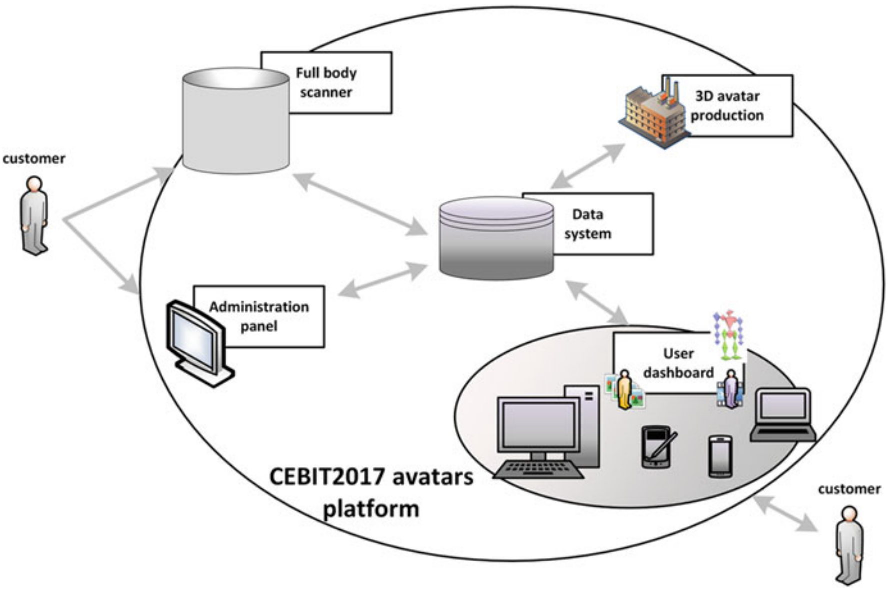

Fig. 5 The architecture of CeBIT 2017 (Doob) avatar platform

distribution. The scanned data is stored in the platform data system. The arrival of new scanned data automatically triggers 2D to 3D conversion processing which is followed by automatic avatar production. Both resulting 3D avatars, static and articulated, are stored in the platform's data system. On demand, 3D avatars are presented to the platform users.

The production of 3D avatars using the Doob avatar platform is done in several steps:

1. Customer comes to the scanning site and registers with the platform with the help of an administrator using the platform administration panel (Fig. 7).
2. The customer is scanned using Doob Group AG's own proprietary scanner named DOOBLICATOR™. Scanning data acquisition is handled by Doob Group AG's proprietary software and then uploaded into the platform data system.
3. The scanned data are processed (Fig. 5), and 3D avatars are produced using Doob Group AG's proprietary software.
4. The customer views his/hers 3D avatar on the avatar platforms dashboard (Fig. 7).

Obviously, the frontend of the Doob avatar platform has two operational modes:

- Administration mode, implemented through the administration panel (Fig. 6)
- Distribution mode, implemented through the dashboard (Fig. 7).

Which operational mode will be active depends on the type of user that is logged onto the platform. The platform login page is presented in Fig. 8.

The administration panel handles user registration and user accounts in general. It enables administrators to monitor processing of scanned data and avatar production.

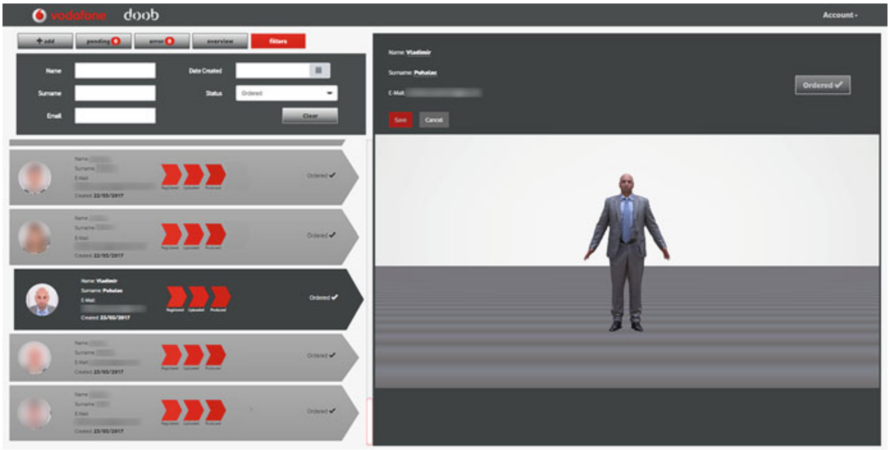

Fig. 6 Administration panel of CeBIT 2017 (Doob) avatar platform (Image courtesy of Doob Group AG)

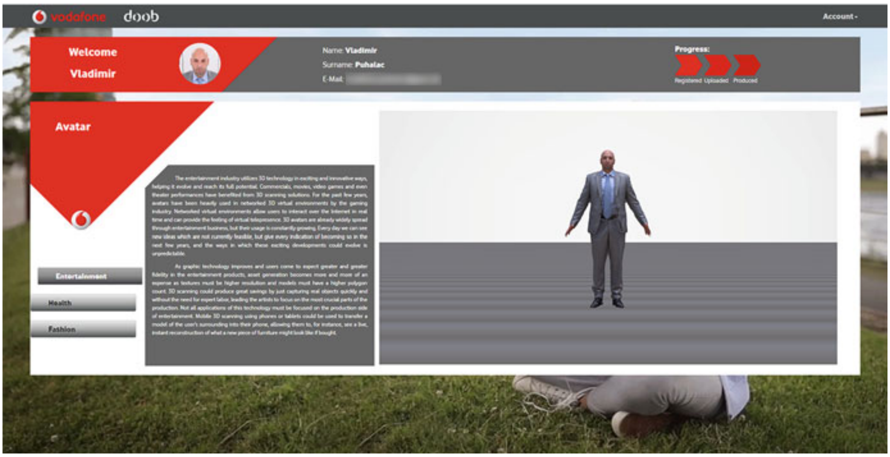

Fig. 7 User dashboard of CeBIT 2017 (Doob) avatar platform (Image courtesy of Doob Group AG)

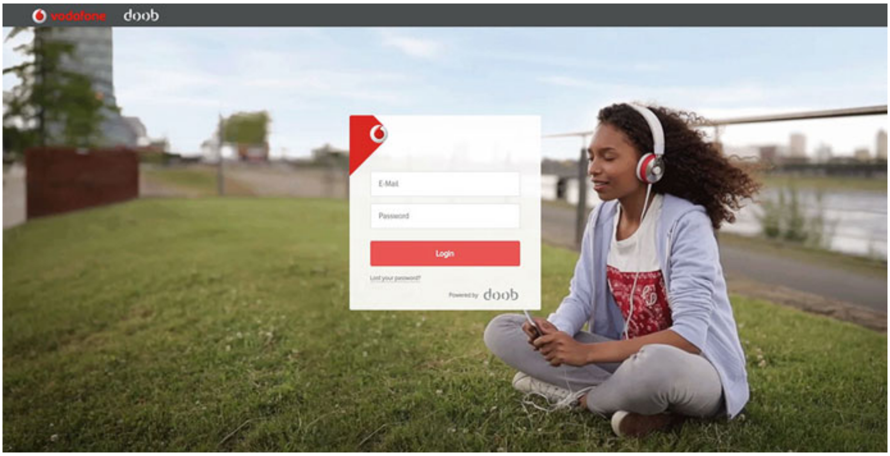

Fig. 8 Login panel of CeBIT 2017 (Doob) avatar platform (Image courtesy of Doob Group AG)

It reports to the administrator when production of an avatar is finished and signals if there are any errors. Administrators can preview customer's 3D avatars and search through the customer base. The administrator platform can be used to communicate with customers.

The dashboard represents the user's view of the platform. The user is presented with their 3D avatar. At the present, the user can interact with their avatar only in a simple way by rotating and zooming the scene. Due to a contract agreement, only the static avatar is presented to the user. Beside the avatar itself, the user is presented with informational content describing future possible uses of 3D avatars in entertainment, health, and fashion. In the future a much richer dashboard will be available to users. It will offer an articulated 3D avatar and several types of interactions with the avatar such as making the avatar move, jump, and similar.

The avatar platform from CeBIT 2017 is a showcase of the platform and therefore does not support any type of monetization. Thus, the download of a customer's 3D avatar is not supported. But the possibility to add web-shop features (purchase and download) is very easy, because the platform has been designed with this feature in mind, and the support for this is already built into the system. At the moment, customers can only order 3D printed figurines of their 3D avatars, using another one of the Doob Group AG's services.

An important feature of the dashboard is that it is built using responsive user interface technology [30]. The customer can use any type of device to view their avatar. This is important because handheld devices represent a huge market and most people interested in 3D avatars are also using smart phones. On CeBIT 2017 virtually every customer asked whether they can view their avatar on a smartphone. From a marketing perspective as well as one of overall user experience and satisfaction, it is good that users can view their avatars promptly, and that they do not have to wait to get home or somewhere else where they have Internet connection and a PC. With the right logistics, such as a cloud-based computer infrastructure, the Doob avatar platform can produce 3D avatars in no more than 5 min. This means that after the customer is scanned, and after a pleasant talk with Doob promoters and/or after reading some promo-material, the customer will receive a message stating that the 3D avatar is ready. The message contains a link to the platform dashboard and the customer's 3D avatar.

The front-end part of the avatar platform is built using standard web-based technologies. Most importantly, the database is built with the future in mind supporting both vertical and horizontal scalability. It is also built to support data mining and big data search engines. At the same time, Doob Group AG's proprietary software implements 2D to 3D conversion and articulated 3D avatar production. This software is implemented to support processing on a single computer, computer network, or on computer cloud system. This represents a remarkable foundation that will allow the Doob avatar platform to become a real gateway for digitizing persons into virtual worlds.

4 3D Avatar Platform Generalization

To fully become a gateway for digitizing persons into virtual worlds, a 3D avatar platform has to offer 3D avatar production, distribution, and consumption services. As the background section demonstrated, integration between the first two services and the third is lacking, especially in the case of realistic 3D avatars.

There are many applications that use generic 3D avatars [4]. The most notable are of course computer games and entertainment applications. It is not possible to clearly categorize applications using 3D avatars as the difference between them is

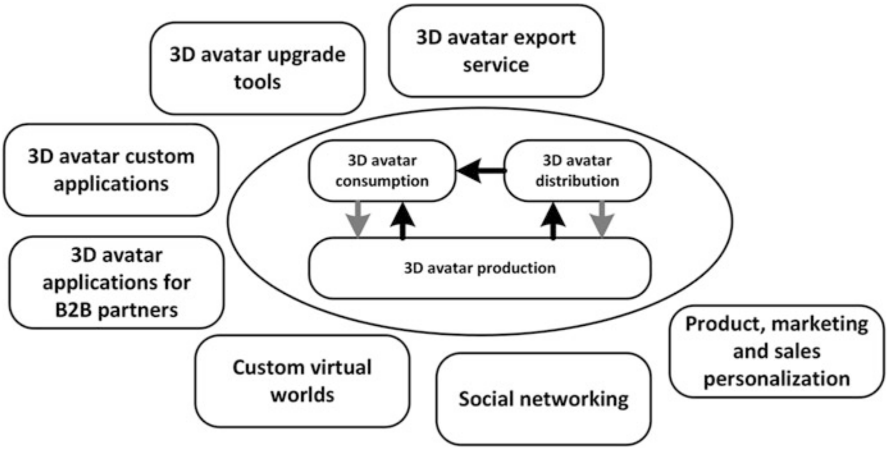

Fig. 9 Categorization of services that a 3D avatar platform can provide

not clear cut. For example, an online 3D computer game such as World of Warcraft and online virtual world service such as Second Life do not differ much. Although the focus of the online games is on gaming and actions performed by the players through their 3D avatars, a lot of social interaction is still taking place. In much the same way, the focus of virtual worlds is social interaction, but the tenants of those worlds are also performing many actions through their avatars such as, walking and dancing. One possible categorization of services that a 3D avatar platform can provide is presented in Fig. 9. In time a 3D avatar platform could include a proprietary version of each of the applications and categories.

As many 3D avatar applications already exist, the first logical service a 3D avatar platform could provide is an avatar export service. This means that customer could purchase a version of his/her 3D avatar specifically rigged for the given 3D avatar application. As this type of services usually implies a partnership between the 3D avatar provider and 3D avatar consumption service, a connection could be made between the 3D avatar platform and that service, which will transform the 3D avatar platform into a portal (gateway) to the 3D avatar consumption service.

The second logical step is to provide avatar upgrade/modification service. Customers will be offered tools which they could use to transform their 3D avatars into anything they like. They could dress them, transform them into fantastic beasts or superheroes, modify their hair style, and similar. Each of these modified 3D avatars could be used in other parts of the 3D avatar platform and sold individually.

The third step in upgrading the 3D avatar platform is to provide its own content for 3D avatar consumption. This can be different applications for different types of devices ranging from desktop computers to handheld devices. The first thing that comes in mind are computer games that can, but do not need to, have a social character. These are the applications that can be provided directly to the customers. They can be completely free for the customers of the 3D avatar platform but with intention to represent content for consumption of the 3D avatars created by customers. The actual game could be free, but the modification of the 3D avatar could be charged. Different types of promotions could be used such as player rating or "collect-them-all" announcements, to motivate customers to create more content.

A 3D avatar platform could also offer applications for B2B partners. The applications would be tailored and branded for the specific business partner, and access would be allowed only to the customers of the business partner. These applications could provide a way for the promotion of the business partner, but the application could also be a tool for expending the business of the partner. The range of the possible applications is quite big. It is possible to offer applications for the entertainment industry (movie and game industries), fashion industry, but also for medicine and education. For example, 3D avatar platforms are natural partners of the fashion industry, because they could offer virtual fitting rooms and human body measurement tools.

Many of the applications can be coupled with VR (virtual reality), AR (augmented reality), and MR (mixed reality) devices such as Microsoft HoloLens and Microsoft Kinect. Imagine what can be all done with 3D avatars in an application that supports these devices. For example, one such application would be a virtual tennis instructor. The user's instructor could be a realistic 3D avatar of Novak Djokovic. He would show the user some move, and then the user should repeat. If the user did the move incorrectly, the application would simultaneously display the user's avatar doing the move correctly and incorrectly. After the user learns all the moves, they could have a match with Novak Djokovic's realistic avatar.

3D avatar platforms could also incorporate virtual worlds of their own or even tools that would allow their customers to create worlds for their 3D avatars. It is possible to build a social network around these virtual worlds and a 3D avatar platform. With scanning technology becoming more and more available and common, the 3D avatar platform could probably gain a significant number of users. With a large user base, it is possible to gather enough data to support personalized sales and marketing, data that could be sold to advertising companies. For example, imagine a situation in which a user of a 3D avatar platform has expressed interest in the merchandise of some sportswear company, or in which all their friends on a social network, bought new sneakers from that sportswear company. That user logs into the 3D avatar platform and sees their personalized advert – an avatar running in these new sneakers.

The technology for all these 3D avatar platform services already exists. Many individual applications are already available or only a step away. Most of the existing applications use generic avatars. For example, the tennis tutor from the previous example would probably use Novak Djokovic's avatar created by a character artist. It would be a near perfect digital representation of the tennis superstar. But the user's avatar would be either generic or generated based on several predefined parameters. The cost of creating realistic 3D avatars for users by character artists is too high. However, the cost of creating a user's realistic 3D avatar using a 3D avatar platform would be comparatively much, much smaller and the entire process would be faster.

The amount of applications for 3D avatars and services of 3D avatar platforms are only going to increase with technology becoming more common and with 3D avatar platform utilization increasing. It is to be expected that 3D avatars will become peoples' virtual representatives on the Internet.

For the end of the section, we will share a vision of a possible future by one of the authors. A user logs into a 3D avatar platform and he/she goes to the 3D avatar platform's application section. There the user starts a furniture shop application from one of the B2B partners. Using their mobile phone, the user scans their room. The user removes their old armchair from the user's virtual room using a 3D avatar platform tool. Through the smartphone, the user sees the room without the armchair. The user browses the furniture shop and chooses a new armchair for the room. He/she manipulates the chair as needed and places it into the virtual room. Then the user walks their avatar into the room and tries the armchair. In this way the user is virtually trying new furniture for free and without putting any physical effort into it. After the furniture application, the user starts an application from a prominent clothing brand. There they get suggestions in buying clothes that match the color and texture of the new armchair. The user's avatar is immediately dressed in the suggested clothes and even shown siting in the new armchair. This is an example how 3D avatars, 3D avatar platforms, and VR/AR/MR technologies are going to transform our future.

5 Conclusion

3D avatar platforms represent an online ecosystem for realistic 3D avatars. In the paper the concept of a 3D avatar platform is introduced, and all the parts of a 3D avatar platform are described. An example of a 3D avatar platform is detailed, one with the potential to grow into a full platform that covers all three phases of the avatar lifecycle: production, distribution, and consumption.

The conclusion that can be drawn from the paper is that, although there are many platforms and services covering one or two phases of the 3D avatar life cycle, there is no 3D avatar platform covering all three phases. However, the underlying technology for implementing a complete 3D avatar platform is already available and becoming pervasive. The first step in providing a 3D avatar platform has already been taken. Various platforms and services are blending together to provide 3D avatar production, distribution, and consumption. Also, the relationship between the various services is by no mean static and linear. Each of these services influences one another and different services require direct support (sometimes it is simple format conversion and sometimes it is a very complex feature set).

For CeBIT 2017 a 3D avatar platform was showcased demonstrating the concepts and possibilities of a 3D avatar platform. This basic platform could easily be extended to a fully functional 3D avatar platform. In a very short time, it could be upgraded to support 3D avatar export to different platforms, 3D avatar upgrade/modification tools, and various 3D avatar applications. Implementing and providing these services represent the future direction of the work of the authors alongside understanding dynamics between the definition, nature, and function of various services of the platform.

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Automated Processing of Planning Modules in Factory Planning by Means of Constraint Solving Using the Example of Production Segmentation

Julian Graefenstein, David Scholz, Oliver Seifert, Jan Winkels, Michael Henke, and Jakob Rehof

Abstract For the adaption of factories, essential data are required as a basis in factory planning. Often these data are either stored in some form, at some location, or on some data medium, respectively, or are not available at all. Preparing these data for the planning process in a planning-appropriate manner can result in high effort. In order to counteract this situation, a data warehouse system can be used in the context of Business Intelligence for initially providing the data in a centralized and consistent form. The advantages of an up-to-date and consistent data base are shown by an example of the production segmentation. With the planning of the factory adaption by means of planning modules, which can be orchestrated individually, it is possible to process planning tasks automatically or partly automated. A given example of a vice production, which can be produced in four variants, was used to show the benefits and explain the approach in detail. Constraint solving, the modular planning process and the data available in the data warehouse enable the segmentation to be processed automatically and thus reduce planning time.

Keywords Factory planning · Planning modules · Constraint solving · Production segmentation · Data warehouse

1 Introduction

Due to emerging and ever-growing circumstances of rapidly changing environment of producing industry, companies have to face the important challenges of dynamic and complexity in order to remain competitive. In particular, shortened and more

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dynamic product life cycles force companies to fundamentally rethink and optimize the reactivity and adaptability of companies and their production systems [1, 2]. Current trends, such as Industry 4.0 and cyberphysical systems, Internet of Things, or digital shadows of factories itself, suggest solutions to problems and challenges caused by massive changes in companies' environment. The interconnection and broad communication not only between people within a production system but also between people and machines enable manufacturers to compete with the aforementioned challenges and allow a variable production focused on variable products up to lot size one which is mandatory for mass customization [3]. Technologies which can share and process information and interact with the physical reality are called cyberphysical systems. An example is an automated guided vehicle (AGV) which can transport material from an individual place to where it is needed. A worker signals the system that he needs a specific item and an AGV will get the item to the worker in the shortest way and time [4]. As every thing is talking to each other in the meaning of Internet of Things, the AGV knows where it can find the item which is the nearest and then navigates by itself to the item and the worker. The problem with these solutions of Industry 4.0 is that they are not directly usable in existing production systems and can only be used out-of-the-box in special cases and therefore require a considerable effort in implementation [5–8, 9]. Especially regarding the preparation for the implementation of Industry 4.0 technologies, many companies are still at the beginning [8, 10]. If such technologies are used, the preliminary step that needs to be completed first in order to cope with the increasingly relevant challenges is to plan the necessary changes or to adapt the own production.

The usage and therefore the necessary implementation of such technologies is one aspect to make mass customization a reality. Before taking the second step, using technologies like cps and others, one has to make the first step – planning the system. If there is no production system, which is capable of competing with the aforementioned challenges in general or no production system at all, the usage of new technology is irrelevant. In order to prepare existing production systems to compete with the new challenges and satisfy the customer requirements, it has to be optimized and adapted for mass customization production. Due to rapidly changing customer needs and therefore shortened product life cycles, changes of the production system have to be made in short amount of time.

In the context of the adaptation of existing factories, factory planning plays a decisive role. To cope with the complexity, the planning process itself has to be shortened and optimized, respectively, by the use of new planning methods. This has to be the goal for the near future in order to be as adaptable as possible on a cost-effective basis. Already through the reorganization or adaptation of existing production systems, inherent potentials in the system can be used to meet cost-effectively the challenges. Therefore, new investments for Industry 4.0 technologies may be avoided in the first place, and the existing resources can be used more efficiently by reorganizing them.

This paper addresses the challenges in adapting the existing factory and production system to new requirements and a new approach to optimize the planning process for this adaption itself. To handle complexity, a specific topic was chosen to demonstrate the possibilities of the new approach. With the production segmentation as one aspect of factory planning and in more detail the parts family formation, the new approach of a modularized planning process is shown. This paper first shows the state of the art of factory planning processes and approaches. It is shown what problems classical approaches have to compete with and why information is one of the most important resources in planning. Second the paper presents the new approach of modularized planning with the support of constraint solving. In the third part, the specific example of parts family formation is presented to introduce the fourth part in which the technical computation will be explained. As a fifth and last part, the following research question will be answered, and an outlook will close the paper.

1. How can structured information improve planning?
2. Can parts of a factory planning process be automated, executed, and calculated?

2 State of the Art

As already mentioned, shorter and more dynamic product life cycles require an increased reactivity for an adaptation of existing systems. Traditional and established factory planning models and concepts are not geared up for the new challenges and are not dynamic in their structure but are more static through the sequential processing of specific planning phases [11–15]. In order to ensure the responsiveness for efficient adaptation planning, more dynamically shaped models are required, which can be orchestrated according to the individual planning case and reduce the planning time to the best possible rate. Some more recent approaches focus on a modularized and standardized process design, in contrast with the traditional, sequential models, and allow for individually orchestrated planning process depending on the planning situation [16–18]. The modular design of planning tasks enables a defined and standardized processing of individual planning processes, which have a certain degree of individuality because of their defined interfaces and input and output information in their arrangement in the planning process [18]. The challenge in planning also includes the optimal combination problem of individual planning modules to optimize the planning time most efficiently and to guarantee the highest degree of responsiveness.

The basis for planning are the data of the company which are necessary for processing the respective planning task, not taking into account if a modular and dynamic or a sequential and phase-oriented structure is used [13]. The necessity of a consistent database in the context of factory planning was already stated in the last decade and created the vision of a concept of the digital factory [19–22]. The efficient use of methods and tools of the digital factory is only possible if a consistent database is also available. Theoretical models, such as VDI guideline 4499 "digital factory," presuppose a consistent database in which all necessary or existing company data are prepared in a data structure – first, to make existing knowledge available to each participant at any time and second, to make the planning itself more efficient. This includes the "standardization of planning processes and their results," the "reduction of planning costs and times through the reuse of models and sub-results," the "increase of planning security through rapid analysis and evaluation of possible planning alternatives," and the "elaboration and reuse of best-practice solutions with regard to models and results" [23]. In contrast to this ideal status of a consistent database, reality looks different. Often the company data about products, processes, and general corporate knowledge are found in numerous file versions of various dates in different formats on a non-specified server and are seldom used. Only when a project starts, the required data for the actual planning are defined and have to be processed first, in order to use them properly. In the worst case, this effort has to be made again for the following project because the data was not kept updated during the time between the first processing initiated by the project and the start of the second project. With regard to Industry 4.0, this lack of data quality and data availability is an obstacle to the use of the associated technologies. The use of cyberphysical systems requires an information and communication system, which is able to process information in real time [24–26]. This necessary prerequisite also offers the possibility to use not only cyberphysical systems but also to profit from prepared and directly available data during adaptation planning. In contrast to that, a completely implemented and, in the context of Industry 4.0, functioning data infrastructure can open up new possibilities. New kinds of data, generated in real time by several cyberphysical objects and other sensor-equipped and communicating technologies, can be used to support the planning process.

An updated and consistent database is therefore necessary for efficient processing of a planning project or adaptation planning. A possible infrastructure for fulfilling these requirements is provided by so-called data warehouse systems. These systems store large amounts of data from different sources and formats and can provide them in a consistent form [27–30]. This offers the advantage of already existing data, for example, from different departments, without the need to be formatted to the same formats. In addition, large amounts of data collected over several years can be processed and made available by using a data warehouse system. A data warehouse is a tool of business intelligence, which is the umbrella term for a collection of other IT-based management tools, and has its origins in the 1990s of the last century [31–33]. The advantage of today's data warehouses is that they can process a much larger amount of data compared to the time they were initially introduced, therefore also gaining more value in the context of factory planning. If the necessary basis for the planning is centrally provided and prepared at any time, new concepts of automated planning can be developed and used [32].

3 Constraint Solving in a Modularized Planning Approach

If the factory planning process is modular, individual planning tasks can be isolated and processed in parallel, considering the dependencies between the individual planning modules. Through the additional use of an algorithm in combination with the underlying data availability, realized by a data infrastructure, such as the already mentioned data warehouse, these planning tasks can be processed automatically or at least partly automatized. Therefore, different planning steps of the factory planning process can be defined as planning modules. These are characterized by a uniform structure which includes input and output information, global restrictions, and a module-specific process structure, which is characterized by processing of different planning tasks. As an example, the production segmentation as one possible task of factory planning provides a separate planning module within a pool of numerous additional modules (see Fig. 1) which can be orchestrated individually to a planning process according to the circumstances of the given planning project. This planning module for the production segmentation is standardized in general, which means that defined input and output information are given, as well as global restrictions. These input and output information and the global restrictions are

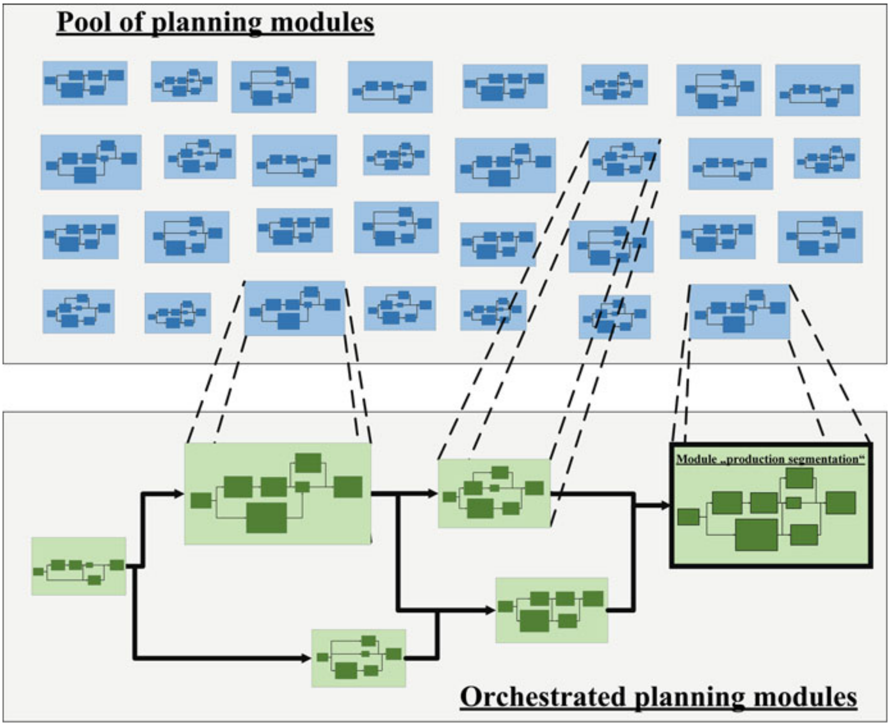

Fig. 1 Pool of planning modules

referred to as local or global constraints. Depending on the individual module, the defined sequence for processing the respective planning modules can be split into further modules whereby each processing step of the defined sequence can be a separate submodule.

Therefore, the orchestration of the individual planning modules can be carried out very finely granular, which allows the highest possible degree of parallelization resulting in a reduction of planning time. Since the necessary input information for processing a planning module is defined and known, this information is retrieved from a specific database (e.g., from a data warehouse) and can be used for processing the planning module. If this input information, which under ideal circumstances already exists, leads to the desired goal of the processing, the planning system can perform this processing automatically. If, however, information is missing or found insufficient, it must be generated by the planner or entered manually into the system. The planning system supports this interference by the planner and the generation of the missing information. Since it is known, which aim is targeted, in this case generating missing or insufficient information, the system can show the planner an ideal way to generate this information by orchestrating the necessary modules. This means that the entire planning can be processed in a partially automated manner. All planning modules, in which the information is sufficiently available, can be edited by the planning system itself to some extent. Only missing information is generated by the designer himself. That way, the planner assists the planning system during the process and even receives support to generate the missing information by the system itself. These interventions by the planner are considered as creative planning tasks, which cannot be processed by the planning system. Therefore the role of the user, in this specific case the planner, is still very important and cannot be substituted by a planning system. As a conclusion, the mentioned planning system functions as an assisting tool for the planner and vice versa.

4 Scenario: Parts Family Formation and Cluster Analysis as Part of Production Segmentation

Being an important component of the structural design, production segmentation is intended as a specific example of the modular planning system presented. Based on established methods of vertical production segmentation according to Wildemann, parts family formation and cluster analysis are done for segmentation using a fictitious scenario. This scenario addresses the optimization of the production of a vise using segmentation. By segmenting the production into smaller, more manageable units, it is intended to reduce throughput times and inventory and to increase the flexibility [15, 34, 35]. The focused product of the vise includes four different variants, which shall be produced using a fixed production program. For enabling various calculations, the applied information and data should be efficiently integrated as input information for the module "production segmentation." For general determination of respective segments, certain information including the plan of action, the production program, and parts lists is required. This data can be used for an automated calculation of parts family formation and cluster analysis with the help of algorithms described by Debnar, Bruestle, and Kosturiak [36]. The selection of suitable algorithms can be characterized as a creative, manual task and cannot entirely be automated [37].

This modular planning system addresses the task of selecting suitable algorithms and involves the user as support for the decision. Subsequently, the modular planning system and the underlying framework can perform the calculation of the respective output information, which finally comprises the respective parts family formation automatically. The aim of this approach in this scenario is to obtain an ideal segmentation of the production by means of certain restrictions or global constraints. In this case, the fixed shift schedules represent a global constraint. This means that the planning system has to make a segmentation, which is aligned according to the existing shift schedules. Depending on the shift schedule – either a one-, a two-, or a three-shift plan – the parts family formation and in conclusion the segmentation are performed accordingly. Taking into account the available personnel and the additional consideration of the production program, appropriate segments can be created. Furthermore, additional costs for night shift allowances and other aspects can be taken into account. Also conceivable are other global constraints, such as the available area or the available budget for possible purchases of machines etc.

5 Constraint Solving Basics

In order to be able to orchestrate individual modules to a processing sequence, the technique of constraint solving as well as combinatorial logic is used. In this section the concept of the constraint solving problem (or constraint satisfaction problem, CSP) will be explained. The aim of this part is to find a solution for a specific problem, which meets all the requirements of the given question.

As a rule, the solution represents a concrete assignment of target variables. The term “constraint” refers to the conditions and restrictions that apply to these variables. Those can be predefined value ranges but also relationships to other variables. For example, the constraint set $\{x + y = 5, X > 1, y > 1, x > y\}$ is applied to the two target variables x and y. Using constraint solving methods, the target $x = 3$ and $y = 2$ can be calculated, which fulfills all given conditions. In this example this is the only solution.

In many cases however it is also conceivable that several solutions exist for a problem. In contrast to other heuristics or optimization methods, apart from the question whether the solution fulfills all constraints, no further statements about solution quality are made. It is not intended to find the best solution possible, but rather to determine whether a solution exists under the existing restrictions. If this is not the case, the constraints are contradictory. For the computer-assisted solution of this kind of tasks, software is already available. The constraint solver “Z3” of the Microsoft Research Group is used for this approach [38].

To use CSP techniques for the orchestration of individual planning modules, Z3 is embedded in a software architecture which implements recursive process. The structure of the architecture is described in the next chapter. The overall process works as follows: As already mentioned, each module has specific in- and outputs. That means that each module has specific preconditions that must be fulfilled in order to execute the module. By executing the module, several post-conditions (that might be preconditions for other modules) are created.

In order for a module to be processed, all necessary inputs of this module must be present. The presence of the data inputs can be modeled as a constraint and can be done either via a Boolean variable or via concrete metric values. If a module is to be executed, it can be checked via constraint solving whether this module is ready.

For the overall process which is to be orchestrated, a target variable is defined. After the specification of this target value, a module is determined which can realize this target value as output. The next step checks whether the inputs of this module modeled as constraint are present in the database and whether the module can generate a solution. If a solution cannot be found, it is determined by stepwise "removal" of individual constraints from the constraint quantity, which leads to the non-satisfiability of the problem. This means that an attempt is made to compute a solution while ignoring a constraint.

This makes it possible to derive which constraints constitute the non-satisfiability of the original problem with complete constraint set. This can be used to determine which input data of a module is missing in the database of the system. These missing data are then interpreted as the new target variables of the module, for which the procedure is repeated. Therefore, again suitable modules are determined, and the nondetachable input constraint of the original module is replaced by the input constraints of the newly determined module. Again, an attempt is made to find a solution under the now-expanded constraint set. The process runs until a solution has been found, i.e., all inputs are completely covered by the data base. This would provide an appropriate starting point for a processing cycle.

The module sequence which has been passed up to then corresponds to the reverse processing sequence. If the constraints of a module cannot be solved in the course of the procedure, this shows that no processing sequence can be generated from the existing information in the data base. In this case, no constraint quantity can be derived from the available modules, for which a solution can be generated, which then requires intervention by the user. This can either automatically remove constraints from the constraint set of the problem in order to generate a solution, or manually enter missing or unpredictable data.

6 Software Architecture

In order to implement the automated approach described in the previous chapter, a software architecture that supports the entire workflow has been developed. The architecture is based on the MVC concept (model / view / controller) established in software development. In this concept, the individual components are implemented in separate layers strictly separated from each other. The lowest layer (model layer) contains the data with which the application works. The controller layer contains the actual program logic, and the view layer is used for the user interaction surfaces. The MVC paradigm allows a flexible program design, which ensures the reusability of the individual MVC modules and complex MVC components as well as a reduced overall complexity, especially in large applications. The following advantages are particularly apparent: The application logic is clearly separated from the data model and the user interactions (Separation of Concern), which allows to use and modify each software component independently. Existing systems can easily be expanded by adding new modules and MVC components.

We used that advantage by integrating several external and independent software components into the architecture. The complete architecture is shown schematically in Fig. 2. The information required for this application is provided in the already mentioned database and forms the data layer of the MVC concept. At this point, all available domain information is stored in the form of structured XML files. Within the XML files, the information is processed in machine-readable form and is provided with all information relevant to the orchestration process. Figure 3 illustrates an example of such a data block.

The XML files can be modified at any time and adapted to changing conditions. In order to differentiate between the various data, the database was divided into at least three different files. Each file contains different categories of information and constraints. These are parts lists, process sequences, and the production program.

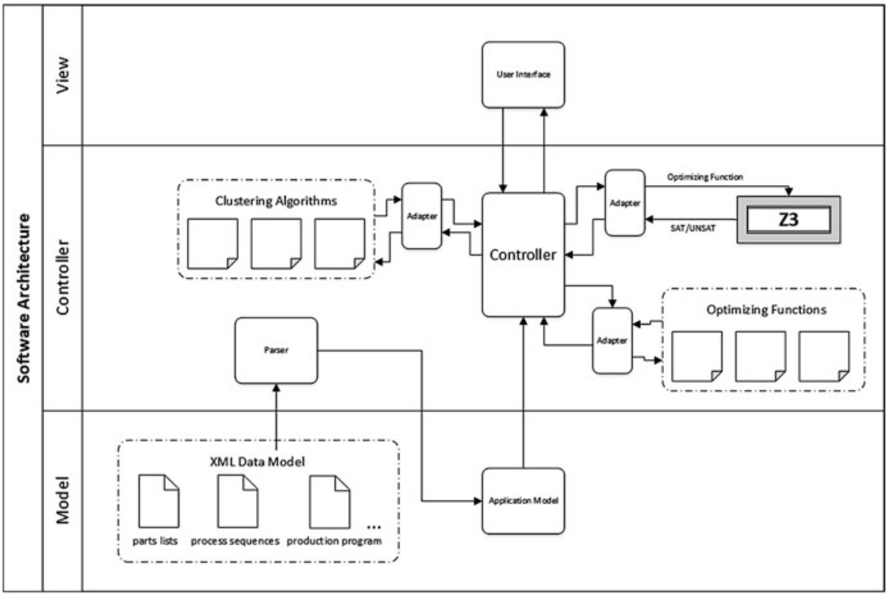

Fig. 2 Software Architecture Scheme

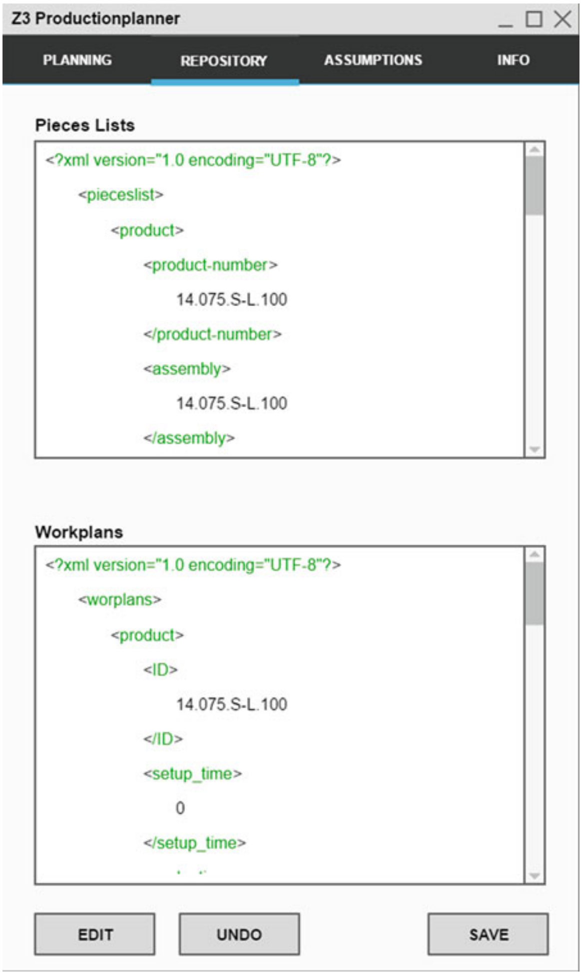

Fig. 3 Example of the XML-Data Model

The XML format offers the advantage that it can be read, written, and understood by both humans and machines. This allows planners to maintain data without the need for extensive IT knowledge and without the use of complex modeling software. At the same time, the format also can easily be generated automatically from other systems (data warehousing) [39].

The data provided in this way is processed by a parser and loaded into the application's working memory. They are available in the form of a dynamic data structure. By means of a suitable clustering algorithm (see chapter "Datamodels for PSS Development and Configuration: Existing Approaches and Future Research"), a parts family formation is already carried out in the existing data. The individual clustering algorithms are modularly available in the controller layer and can be freely selected and exchanged. We implemented a universal adapter that allows us to add and remove clustering algorithms dynamically as long they are implemented in JAVA. The user can later choose which algorithm is to be used. There is also an adapter available that provides the opportunity of adding several individual optimization functions to the software. These functions are used to calculate the desired target variable and are to be computed and validated by the Z3 constraint solver.

In the view layer, the user enters a desired calculation target and some of the selected conditions by means of a graphical user interface (GUI). The inputs are then recorded and processed by the controller. The controller then collects the needed data and the desired clustering algorithm and optimization function to create the quotations and functions that represents the desired calculation target and the constraints that exists in the given domain.

If the user wants to calculate, for example, the number of shifts required under a given number of machines, he specifies this in the interface. The number of layers is defined as the target variable to be calculated and the number of machines as a constant constraint. It is also possible to specify the number of machines as a limit value, which must not be exceeded. In this case, the actual number of machines is variable, and a concrete solution would then also be calculated. The software now builds a matching optimization function from the individual modular components. Let's assume the user wants to use a very simple optimization function like $\{x = (x_{\mathrm{M1}} * a_{\mathrm{M1}}) + (x_{\mathrm{M2}} * a_{\mathrm{M2}}) + ... + (x_{\mathrm{M}n} * a_{\mathrm{M}n}); \min(x)\}$, where x_{Mi} = number of shifts required for a machine Mi and a_{Mi} is the number of machines of a certain type Mi, which are used in the given production program. While each a_{Mi} is known by the specified restrictions of the user, each variable x_{Mi} must be calculated using information from the database. As a result, the software substitutes, by means of knowledge from the data base, each variable to be calculated by a function, which provides the desired variable as a result. If this function also contains unknown (and still to be calculated) variables, the procedure for this variable is repeated. This results in a systematic complex optimization function and a set of several constraints that covers the entire problem area.

If a variable is found, for which there is no calculation basis for the database, the planner is informed that he must supply the relevant information. The already mentioned problem of the nonexistent data basis is partially solved in the current scenario (XML data available). Although there is information on parts lists, plans of actions, and shifts schedules, it does not contain the existing machines. Despite the fact that this information is available somewhere in the company, it is unfortunately not stored in a central database and processed for use. This missing information can imply additional, unnecessary effort to implement the data, which could have been avoided in advance by a consistent data management.

The step by step substitution of variables usually results in a complex function with several limitations and constraints regarding this function. The function and the constraint set are then sent to the constraint solver Z3. Z3 now calculates whether this formula can be satisfied and returns SAT for a satisfiable or UNSAT for an

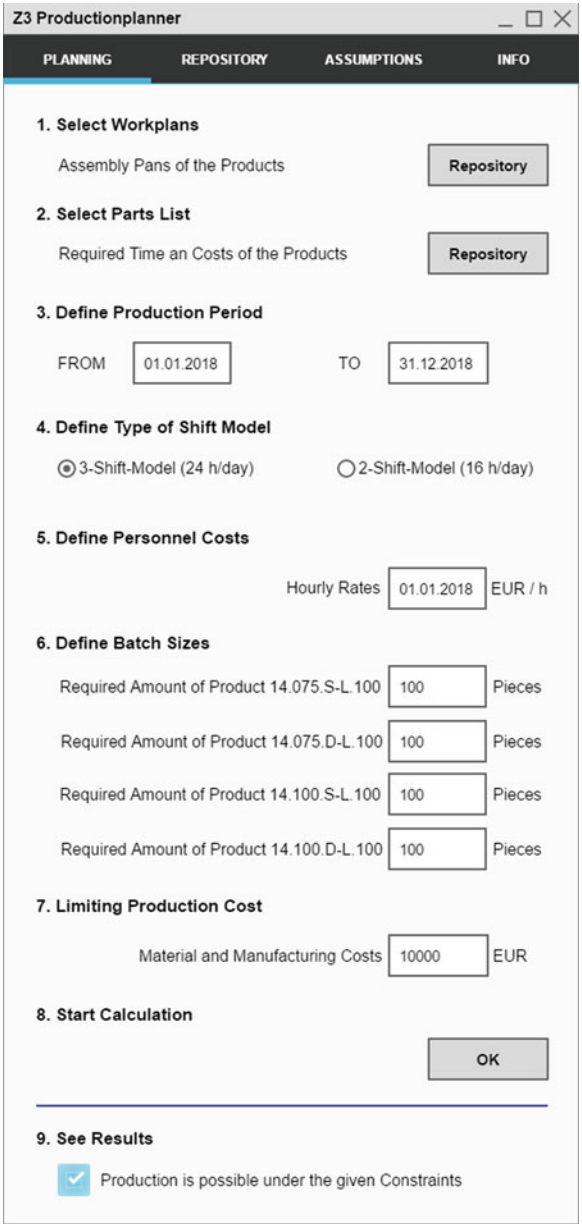

Fig. 4 User Interface with validated result

unsatisfiable formula. If the formula can be fulfilled, a valid variable assignment of all variables including the target size is output (see Fig. 4). With this solution, the planner can then continue to work. If the formula is unfulfillable, this means that the desired calculation target cannot be realized under the given conditions.

7 Summary and Outlook

The described work illustrates that with the help of a consistent database and a specific software architecture, the aforementioned planning modules in the specific scenario can be processed automatically. In the described example the planning module “production segmentation” was used to clarify the functionality of several in- and output information of the planning module itself in combination with the available data and the computing software which answers the second research question. The lack of information is one of the main problems for the planning system. Only with the assistance of the user the planning system can work properly. That clarifies the circumstance that the user and the planner, respectively, play a decisive role in the presented system. As mentioned before, the data provided for the whole planning process is crucial and has to be provided in short time. Therefore, the usage of a data infrastructure as provided by a data warehouse would be suitable. The ideal case would be a data system that provides needed data in a consistent and prepared form in real time. This would mean that planning data is always available at any point, which could drastically reduce time of planning. It also answers the first research question which was formulated in the introduction. Structured information can optimize planning time and reduce cost in a very efficient way. Without the effort to gather data for every new project over and over again, it is possible to start with a project more quickly. Especially for the usage of the presented modular approach, a structured database like the aforementioned data warehouse is mandatory.

The presented planning system with the underlying software architecture is not only suitable for assisting and automatically processing the planning task “production segmentation.” It works for a wide range of different planning modules, which can be added to the system. Therefore, the software architecture is also built in a modular manner. Different modules for optimizing different aspects, like in these example algorithms for parts family formation and cluster analysis, can be added with less effort. The decision of whether to choose one or another optimization tool belongs to the planner. In the future development, the software is also to provide detailed feedback on the reasons for the nonfulfillment of a function in order to give the user recommendations for adjustments. Other data categories like 3D data of the machine pool or the factory building could also be considered to be added to and evaluated by the system. With this evaluation and the preparation of such data, respectively, in a form usable for the planning process, it could support reducing the planning time. With that knowledge, the user and the whole system can be developed to a further stage of precision.

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A Digital Fabrication Infrastructure Enabling Distributed Design and Production of Custom Furniture

Andrea Barni, Donatella Corti, Paolo Pedrazzoli, and Diego Rovere

Abstract Thanks to the implementation of advanced technologies within simple-to-use responsive design interfaces, everyone can now purchase perfect-fit products from home. This is possible in several sectors, thanks to the great developments in information and communications technology (ICT) and the wide use of cloud computing. The furniture sector is yet scarcely influenced by this trend, still lacking of systems able to translate parametric design libraries in optimally scheduled, ready to be manufactured projects, correlated by list of operations and specifications for on time customers' order fulfilment. This paper aims at describing an application model of the mass customization paradigm within the furniture sector, focusing on field-level solutions implemented to create a fully operative "design to manufacturing in one step" process. The integration of several software tools, market ready or specifically developed for the need, paved the way for the design of a seamlessly integrated production system able to manage the complexity of a mass customization environment. The proposed IT infrastructure is intended to run distributed design and production facilities fulfilling the requirements of a highly variable customer demand both in terms of product requirements and buying experience. The developed system has been tested within the context of a shopping mall where the design area and the manufacturing site have been installed for several days.

Keywords Digital manufacturing · Furniture customization · Distributed production system · Urban manufacturing

1 Introduction

The popularity of mass-customized (MC) products has been growing in both product and service industries [1], leading to a rising level of expectation from customers' side. As articulated by Pine in its recent analysis [2], while if we date back to 1993,

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mass customization was considered “the new frontier in business competition”, today, it is an imperative in industry after industry to discover and fulfil the multiple markets within each customer.

To achieve such expectations, the value chain has to be tailored to the creation of an infrastructure supporting the design, proposal and development of customers’ co-created products [3]. In particular, it is necessary to create a seamless process to satisfy customers’ expectations, typically starting from a digital interface that directly interacts with the production line enabling the achievement of the same economies of scale as mass-produced products. In parallel, it is necessary to create a competitive cost structure compared to non-customized production processes even if the manufacturing infrastructure becomes more complex. Success in mass customization manufacturing is indeed achieved by swiftly reconfiguring operations, processes and business relationships with respect to customers’ individual needs and dynamic manufacturing requirements [4]. According to Fogliatto et al. [5], this can be done leveraging on four main enablers supporting the full implementation of mass customization (MC) logics: information technologies (IT), manufacturing technologies, methodologies and processes. In this paper the attention is paid, in particular, on the first two enablers. Considering the recent developments in the IT sector, several efforts have been spent in the design and development of sales configurators and/or configuration toolkits [5–7], software applications meant to support a customer or a sales person interacting with a customer, to specify the customization details required to match customer requirements with the solution space of a company’s mass customization offering [8]. Their fundamental function resides in presenting a firm’s product offering and guiding the potential customer in specifying a complete and valid solution [9]. If these tools are provided as an online mean, usually they enable customers to order customized products online, instead of printing or sending product configurations to retailers [10].

The information gathered with the sales configurators must be thus structured and conveyed to the production system, in order to trigger the data management flows supporting the fulfilment of orders. The required level of integration of the ICT system is thus particularly relevant for those companies willing to succeed in products customization. In particular, the so-called horizontal integration is an integration of machinery so that parts and components are automatically passed from machine to machine and the machines know either from the manufacturing execution system or from the part itself what they have to do with those parts or components [11].

A recent research (2015) of the Boston Consulting Group [12] also highlighted how Industry 4.0 allows for a faster response to customer needs enabling a new level of mass customization. Without the adoption of the Industry 4.0, there is a lack of integration not only among companies, suppliers and customers, but also departments such as engineering, production and service are not closely integrated. Vertical integration and horizontal integration are seen as a lever to transform industrial production towards a higher responsiveness to individual customers’ demand. The exploitation of the Industry 4.0 potentialities is seen as an enabler of mass customization by Zawadzki and Zywicki (2016) too [13]. They believe that, in order to overcome the challenge of an effective implementation of mass customization, it is necessary to build smart factories relying on smart product design and smart production control. From the design point of view, they advocate the deployment of knowledge-based engineer system, whereas for the smart control, the synchronization of material flow in the production system is considered as essential.

Factories manufacturing mass-customized product must thus become smart by setting up flexible production systems able to reconfigure according to the variations of lot 1 production [14]. Moreover, since customers usually have to wait longer if they want personalized products, to maintain a competitive advantage, they have to increase the agility of their production processes [15].

Digital manufacturing (DM) recently raised as one of the technological enablers supporting the transition towards smart and agile manufacturing [16]. DM consists in a set of processes and technologies which employ digital algorithms to turn a digital file into a particular form of structure through either additive or subtractive operations on physical materials [17]. The process starts with the design of a digital 3D model of the object that is thus manufactured using a machine operated by computer. Additive processes use technologies that, starting from the digital design, decompose it in layers that are laid down in a layer-upon-layer fashion to fabricate the 3D object.

Still starting from the digital representation of the final object, subtractive processes work by successively cutting material away from a solid block of material.

Digital fabrication is becoming an integral part of mass customization because of its quick customization capabilities, flexibility, decentralization, cost and its continuous development. Using a customization platform, users can input their options and specifications into a configurator. Production processes such as 3D printing and CNC machining can then develop these models with quick production times and minimal waste [18, 19].

2 Digital Manufacturing in the Furniture Sector

In the furniture domain, the adoption of digital manufacturing technologies is still scarce. The market is dominated by two types of business models: companies manufacturing mass-customized products of different quality level to be sold in brick and mortar stores and craftsmen realizing personalized solutions fulfilling specific customer needs.

The grey area among these two solutions is still scarcely addressed. Few examples come from companies trying to leverage on design of 3D objects, and digital manufacturing have recently risen. One of these is ATFAB [20], a company that designs customizable furniture specifically designed to be manufactured exclusively through CNC machine tools. The developed projects are engineered to be available directly from the buyer, based on settled Fab Lab networks, or selecting a manufacturer in their own area, connected to the Opendesk platform. In this way, the company outsources every stage of the production process beyond the product design, focusing on solutions optimized for this type of model. Two more examples that use digital technologies to create customizable/personalized products are the Opendesk platform [21] and FabHub [22]. Both dedicated to networking consumers, designers and local producers, Opendesk bases its business model on the marketing of production projects using digital manufacturing technologies, relying almost exclusively on products that require the use of wood panels with limited final treatments and can be made locally by producers in the area of consumers. The second platform, on the other hand, promotes the access of experienced designers or consumers, to digital manufacturing technologies, through networking of makers, workshops, companies and manufacturers offering production capacity or services based on digital manufacturing technologies.

The examples above represent just few of the recent attempts to build on the adoption of digital technologies to transfer to the customer the co-creation potential and maintaining a competitive advantage on manufacturing. As mentioned above, to achieve these results, the development of a production system able to integrate digital manufacturing technologies with flexible and agile production techniques and co-creation toolkits is a fundamental requisite to create a self-sustaining business model.

Despite relevant efforts in the industrial and academic domain, the implementation of business models based on mass customization is still very complex. According to Suzić et al. [23] companies still suffer from a lack of guidelines and supports that help them in the process of implementing MC objectives, thus limiting the spreading of such production models.

The aim of this paper is thus to give a concrete support to the ongoing research by describing the development of a production system relying on the integration of digital technologies for the manufacturing of customized furniture.

3 A Digital Manufacturing Infrastructure for the Production of Mass-Customized Furniture

The developed production system is composed of two main components that can be flexibly reshaped in order to meet different market requirements: a configuration toolkit, supporting the customization/personalization of furniture, and an automated manufacturing system relying on CNC technology, enabling lot one production of customized furniture.

3.1 Overall Architecture

The integration of the configuration and manufacturing systems is carried out through the adoption of an IT infrastructure (Fig. 1) able to handle automatic furniture production, starting from the order acquisition of a customized piece of furniture, down to the machining and delivery management.

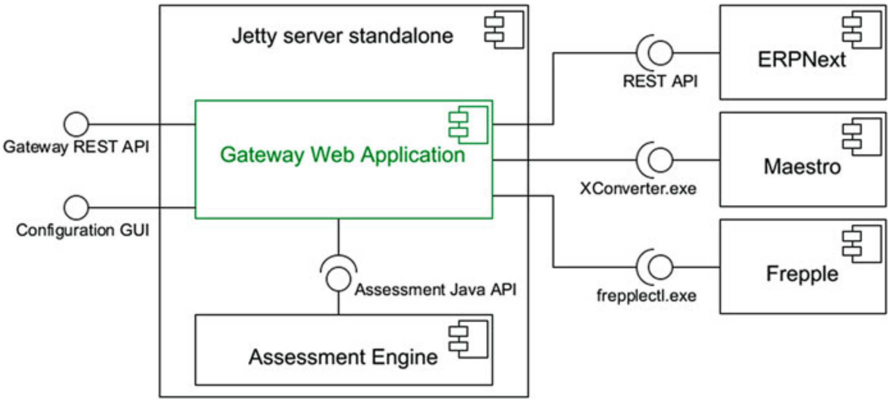

Fig. 1 Software modules constituting the IT backbone of the production system

The IT infrastructure is composed of several software modules, respectively, addressing product configuration (Configuration Toolkit), execution of CNC machine orders (Maestro), resource planning (ERP Next), production scheduling (Frepple) and assessment of environmental impact of developed products (Assessment Engine). In the proposed solution, the core function of supervising the overall system, acquiring data from the production systems components and dispatching them, is centralized in a web application running on cloud infrastructure called Gateway. The main objective of this tool is to reduce the need of developing inter-component communication interfaces, centralizing them in a single module.

For each of the aforementioned components, a brief description is proposed hereunder.

Configuration Toolkit

The adopted configuration toolkit has been designed relying on a Topsolid Wood configuration platform. The tool is meant to support the definition of the order, guiding the customer along the process of customization. Receiving as input customers' requirements, it provides as output on the bill of materials (BOM) and, through the embedded postprocessor, generates manufacturing data to be managed by the CNC machine. In the current architecture of the software solution, the configurator interfaces only the Gateway component, which also provides to the configurator APIs for order creation and customers management.

Maestro

The CNC machine adopted has been derived and upgraded to manufacturing requirements from a SCM Planet P800. Maestro is the SCM proprietary software, normally running on the CNC, that provides high level interfaces to control the operation of the machine tool. The instance of Maestro represented by this component is instead used locally, in batch mode by the Gateway, to mimic the behaviour of the machine tool, in order to calculate nesting of parts and foresee machining time. Maestro directly interfaces with the numerical control of the machining centre that covers the main tasks of a fully automated woodworking system module for panels based furniture manufacturing (charging/discharging, nesting, routing, boring, milling and edge-banding). Gateway feeds numerical control with part programmes for part machining.

Frepple
Frepple is the scheduler component responsible for the management of the production scheduling. It receives form Gateway the list of tasks to be carried out for the production of the order, calculating production queue and expected delivery times.

ERPNext
ERPNext component acts as the ERP of the developed production system, providing means to manage all the resources needed for the operation of the mini-factory. This component is constituted by an instance of the open source module ERPNext (https://erpnext.com/) tailored to the requirements of the developed production system, basically addressing the management of customers' records and orders, supply chain management and inventory management.

Assessment Engine
The assessment engine is an "in-house" developed software tool responsible for the assessment of the environmental footprint of the customized product. Through the Gateway it receives the data related to material of the parts, material of hardware and edges, operations performed on parts and environmental indicators of the material suppliers and provides as output a list of environmental indicators characterizing product footprint.

Gateway
Gateway component acts as the integration layer of the software architecture since it is in charge of interfacing all the other components controlling the principal order management processes within the mini-factory.

3.2 Data Management and Production Flow

In practical terms, the management of the data within the production system is arranged as follows. The customers' data acquired through the configurator are passed by the Gateway to ERP Next that stores them and begins the creation of the sales order to which the final BOM will be attached. Once the order is launched, the production order is contextually prepared, linked to the previous sales order. A buying order for the raw material composing the product is eventually generated. Once the product is configured, it receives a BOM containing the configured element, composed of a certain number of parts, including hardware and edges. For each part to be manufactured, the Gateway receives also the scripting files defining the machining operations of each part and eventually returns to the configurator the expected delivery date, calculated considering the already existent manufacturing load and the time necessary to manufacture the furniture. In parallel, the Gateway shows through the configuration toolkit the calculated price (updated at each iteration during product configuration), the expected delivery date and the environmental impact calculated for the configured product.

Once finalized an order, the PGMX files required to manufacture the product are generated and dispatched to the machine tool SW. The files are thus used to nest the programmes. This operation is intended to enable the minimization of the scrap rate and to create the raw material list to be communicated to the ERP for raw materials order. Through the connection with the Maestro SW, the overall manufacturing time required to bore, mill, cut and edge band all sheets is eventually calculated and used to calculate the precise delivery date as described in the previous section. The connection with the scheduler enables to generate and store the tasks required to manufacture the defined furniture. Considering the estimated raw material arrival date and the expected manufacturing time, the scheduler is able to define a production queue, thus retrieving the expected manufacturing date and the delivery due date to the customer. The last iteration is carried out in order to generate the environmental impact data relative to the manufacturing of the configured furniture. In order to do so, the Gateway communicates to the assessment engine the data related to material of the parts, material of hardware and edges, operations performed on parts and environmental indicators of the material suppliers. The impact data are thus used for the generation of the CTC label that is attached to the manufactured product providing information about the environmental impact of the produced piece of furniture.

3.3 The Gateway Data Model

The Gateway data model represents the common shared representation of the data entities needed to support operations of the described manufacturing system. Since the component is central to the whole operation of the mini-factory, it holds and maintains the common shared view on the production orders that can be accessed by all the other components (Fig. 2).

This section describes the structures and formats supporting the order management by the Gateway component in the Gateway data model.

CodedItem is an abstract base class that extends almost all the relevant items of the customized order. It represents a generic object managed by the software infrastructure identified with a unique string code within the whole order management system.

The class *FurnitureOrder* represents the root data structure to manage a production order within the manufacturing system. This structure, which is populated during several steps of the order management process, contains all the information about the final customized product, shared by the components of the software architecture. FurnitureOrder is an extension of CodedItem.

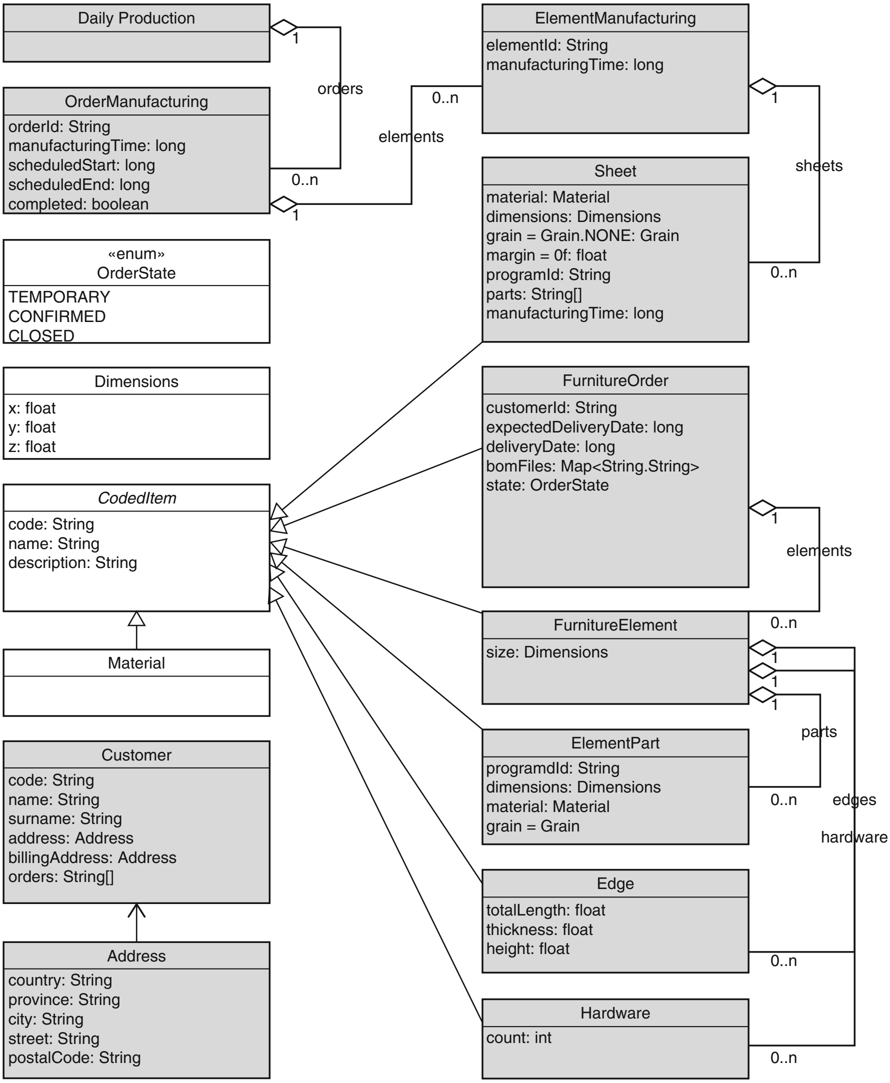

Fig. 2 Gateway data model – class diagram

Considering that an order can be composed by more than one piece of furniture, the class *FurnitureElement* represents a piece of the furniture order (a cabinet, a table, etc.). FurnitureElement is an extension of CodedItem.

The class *ElementPart* represents a piece of the furniture element (shoulders, top, bottom, etc.). ElementPart is an extension of CodedItem.

The class *Edge* represents the amount and type of edge used in a furniture element finishing. It is mainly used to keep track of the total edge usages, in order to plan stock reorder. ElementPart is an extension of CodedItem.

The class *Hardware* represents the hardware elements necessary to assembly a FurnitureElement. ElementPart is an extension of CodedItem.

DailyProduction is the class representing the queue of orders expected to be covered in the daily production.

OrderManufacturing class contains all the data for manufacturing the parts of an order. The related FurnitureOrder instance is not directly referenced here. Instead a loose relation is kept here using the order id.

The class *ElementManufacturing* contains data needed to manage the production, on the machining centre of all the parts of a FurnitureElement. These data are generated during the nesting procedure and managed by the Gateway in order to feed the production system of the mini-factory.

The class *Sheet* represents a wood panel which is used as the starting raw material for the manufacturing process. Each Sheet is used to manufacture one or more parts according to the results of the nesting process. Sheet is an extension of CodedItem.

The class *Material* models a coded material for panels, parts and hardware. FurnitureOrder is an extension of CodedItem.

Dimensions is a utility class representing the extensions in the three coordinate directions of a simple bounding box.

OrderState is a utility enumeration that is used to indicate the current order state.

The class *Customer* represents a CTC mini-factory customer and contains the data required to profile the subject for starting a furniture order.

Address is eventually a utility class to represent an address in the customers definition.

3.4 Order Acquisition Process

The interrelation among the different software tools can be highlighted in the following UML sequence diagram describing, as example, the process of order acquisition. The process takes place whenever a customer starts a furniture configuration session and ends with the scheduling of a time slot for order manufacturing. The following paragraphs provide a detailed view of the steps of the process describing the messages reported in the sequence diagram of Fig. 3.

The first invoked function (CreatOrder) triggers the elaboration of the order data. Starting from a full definition of a BOM from a piece of furniture, the function computes manufacturing details in order to get a probable order finish date. In order to identify the amount of material required to manufacture an order, the procedure calculateNesting calculates the nesting of the parts of a single element. The nesting starts from the definition of the list of available sheets and the part programmes (in PGMX format), as well as the configuration options, and generates a list of required panels, related machining programmes and indicators (e.g. scrap

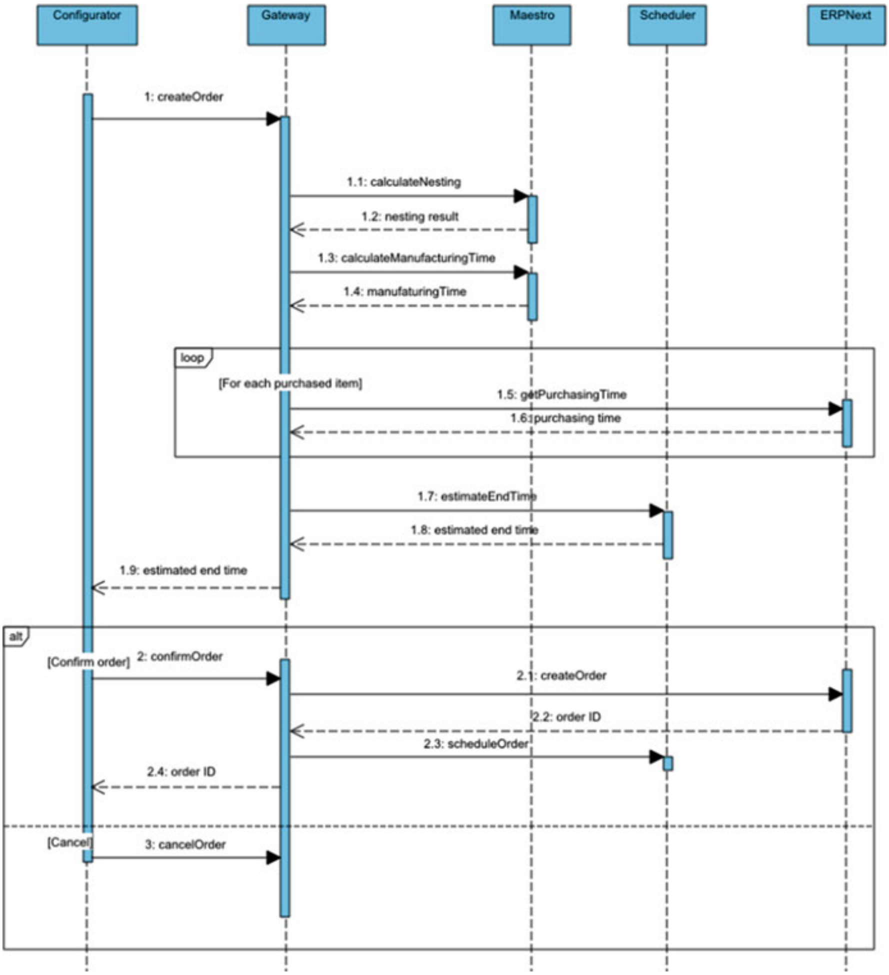

Fig. 3 UML Sequence diagram of order acquisition process

level). Nesting is performed only on the parts of a single element, ensuring that no parts from different elements are mixed together on the same raw panel. This approach is meant to strongly simplify the following procedures and, in particular, to significantly reduce the amount of space required for packaging. Nevertheless, in order to avoid an unsustainable level of scrap, the nesting process tries different scenarios of input panels, extracting them from the set of available sheet sizes provided by the suppliers, assessing them and choosing the one with the lowest scrap level.

In order to properly allocate the order in the queue, *calculateManufacturingTime* calculates the manufacturing time of a set of specific part programmes taking into consideration the features of the target machine tool. In parallel it's necessary to retrieve the data about state of the inventory and the time necessary to the supplier to deliver the required materials. *getPurchaseTime* is thus dedicated to retrieve the current updated value of the purchasing time of a specific raw material. Gateway uses this information in order to evaluate the longest purchase time among the entities of the whole BOM. With this set of information, *estimateEndTime* is meant to calculate the earliest production end date of the order. Gateway uses this information in order to provide the configurator (and then the customer) with a reliable estimation of the delivery date.

createOrder, *confirmOrder* and *scheduleOrder* are, respectively, dedicated to (i) create an order on the ERP. Until the customer checks out, the furniture order is considered temporary and therefore kept locally at Gateway stage; (ii) transform data of the temporary order used for time and delivery date estimation into a real production order that is fed to the mini-factory system; and (iii) ask the scheduler to insert the order in the production scheduling.

If, for any reason, the customer does not confirm the order, then configurator removes the temporary order from the resources managed by the Gateway through *cancelOrder*.

4 Scalability of the Implementation Scenarios

The proposed technological infrastructure can be deployed in several scenarios, according to the business model it has to be applied to.

Two possibilities of implementation have been formalized. The first one (Fig. 4, case a) envisages the collection of production orders by means of distributed shops and online e-commerce facilities. The integration among the web market and the real shops is intended to exploit the different customization capabilities that can be offered by the proposed technological infrastructure. By means of the web application, the customer can access to simple customization parameters, namely, addressing the tailoring of dimensions, colours and materials. Personalization can

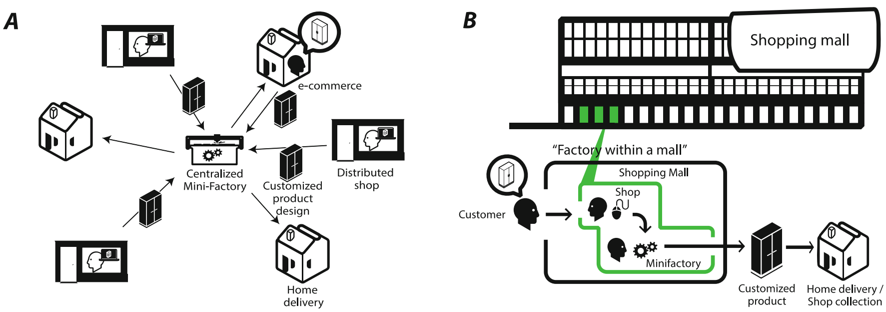

Fig. 4 Envisaged implementation scenarios: centralized mini-factory serving distributed shops and e-commerce (**a**); urban manufacturing in a shopping mall (**b**)

be although technically reached by means of the interaction of an expert user in a dedicated shop. Advanced functionalities of the configuration toolkit managed by an expert user can thus give the access to images and letters engraving and freeform shapes modification.

The collected orders can be thus manufactured by a centralized production system able to fulfil orders coming from a variable number of customization inputs. The integration in a network of distributed mini-factories, as proposed by Seregni et al. [24], should provide the economy of scale providing the sustainable exploitation of the concept.

The second scenario (Fig. 4, case b), fully described by Barni et al. in a previous work [25], is intended to exploit the proximity to the urban area to foster urban manufacturing close to the customers. The proposed model envisages the installation of both the shop and the production system in an integrated mini-factory scenario. Unlike for the first scenario, in this case the main aim is the closeness to the customer and their purchasing experience. Additional value is brought also by the use of a local supply chain that not only allows shorter lead time but also a higher level of sustainability.

4.1 Implementing the IT Infrastructure in a Shopping Mall

In order to test the validity of the developed IT infrastructure and of the related business model in offering mass-customized pieces of furniture, a demonstration activity in a real context has been set up. The idea was to allow a customer to configure his/her product, look at the production process, if of interest, and have the product delivered in a short time. A mini-factory has been installed in a shopping mall located in the Milan area (Italy) for a period of 11 days in April 2017. The selected mall, opened in 1975, is one of the oldest shopping mall in the Milan area and features an average affluence of 6.500.000 visitors per year. The types of products manufactured by the demo factory, namely, bedrooms for children and living rooms, made this location ideal to reach target customers: young and middle-aged people with children potentially willing to pay a premium price for a higher level of customization and who are aware of sustainability issues. During the demo quantitative and qualitative data have been gathered to analyse both the behaviour of the system and the feedback from potential customers. In what follows how the demo has been organized is described before analysing the main obtained results.

4.2 The Mini-factory Organization and Customer Experience

Within the shopping mall, the mini-factory demonstrator has been organized around two blocks: one in the parking area for the manufacturing system positioned below a tenso-structure (see Fig. 5) and one inside the shopping mall where the corner shop has been installed (see Fig. 6).

Fig. 5 Manufacturing system deployed in the shopping mall scenario

Fig. 6 Deployment of the configuration platform in the shopping mall scenario

The configuration toolkit was installed on desktop machine connected via USB to a rooter providing connection to the local wireless network. The rooter also provided a local network required for the connections among the computer running the configuration toolkit and the tablet serving as user interface for products customization. At CNC machine level, an internet connection was set up using a 4G-based mobile solution.

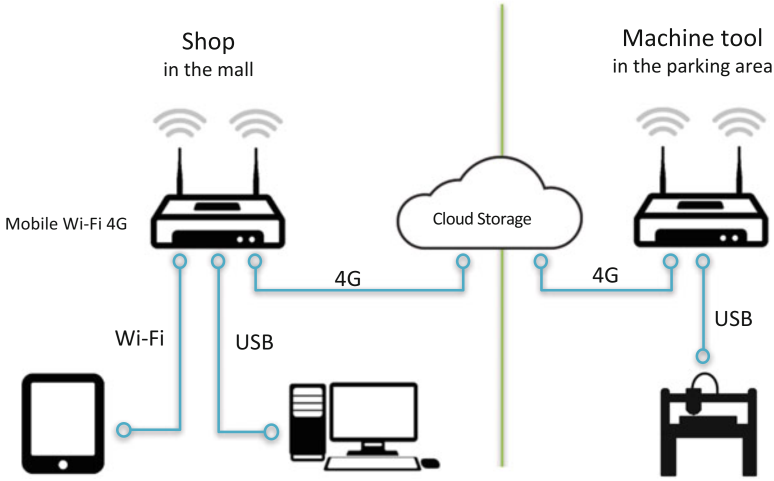

Fig. 7 Deployment of the IT infrastructure in the shopping mall context

Configuration and manufacturing system were thus connected to a cloud infrastructure supporting the operations of the Gateway (see Fig. 7).

In order to fully demonstrate the feasibility of the “design to manufacturing in one step” concept, a simple product type with few parameters of configuration and light enough to be easily carried by customers has been chosen, a family of cabinets. They can be customized along the following dimensions: height, width and depth, number of drawers (one, two or three) and combination of colours for the front of drawers.

Relying on the developed IT infrastructure described in the previous sections, the customer experience from the configuration to the recovery of the manufactured product takes place following the next steps: the customer approaches the CTC shop, and he/she is received at the CTC desk where he/she is supported by the shop operator in the configuration process based on the use of a tablet running the touch planner. A monitor shows, at the same time, the rendering of the configured product so that the customer can have an immediate idea of how the selected product looks like. Once the desired configuration has identified, the customer submits the order (Fig. 8).

The order submission triggers a set of tasks among them, the main ones being the generation of the machine code, the update of the ERP for possible replenishment and the calculation of the sustainability performance of the selected configuration. Thanks to the results of these tasks, the customer is provided with the promised due date that is displayed on the configurator. Due to the demonstration aim of the mini-factory, products are then gifted to customers, but the system is also able to provide at this point also the price of the product. At the same time, an email is sent to him/her (a registration has been asked at the beginning of the configuration process)

Fig. 8 Configuration desk installed in the shop

with the order confirmation, the assembly instructions and the environmental tag showing the results of the sustainability assessment. Finally, the customer is given a ticket to recover the product from the factory once ready.

The customer receives the disassembled product and takes it at home where he/she is supposed to assemble it on his/her own supported by the assembly instructions sent by email in advance.

4.3 Assessing the IT Infrastructure Implementation

The demonstration experience carried out in the shopping mall validates in a simplified environment how design and production of customized items are seamlessly integrated, thanks to the proposed IT infrastructure shortening, in particular, the time between the product configuration and the product delivery. Data gathered during the running of the demonstration through the software systems managing the whole production system (Gateway, Frepple, ERPNext, Topsolid, Maestro) can be analysed to better grasp benefits and possible criticalities of the proposed solutions from the production point of view. Table 1 summarizes values of the KPIs calculated from this data set.

Table 1 Main performance indicators obtained in the demonstration

KPI	Unit of measure	Average value
Number of fulfilled orders	N°	62
Average inventory value	Days	4.1
Non-value added time	%	19%
Delivery time	Days	2.23
Quality level	%	58%
Throughput	Orders/hour	0.49
Average energy consumption	KWh	23.8

The overall behaviour of the production system can be considered consistent with the expectations guaranteeing an average delivery time of 2.2 days. Nonetheless, the average production time, and consequently the throughput value, was not as high as expected. This is because the performance suffered from the ramp-up phase that, due to the limited time of the demonstration, hugely impacted on the system performance. In particular, two improvements could be easily foreseen towards a smoother flow of activities with a longer experimentation: the optimization of the manufacturing operations sequences and the increase of the quality level.

In order to collect also the customer satisfaction, each demonstration participant has been asked to fill in a questionnaire addressing topics such as the configuration experience, the production and delivery time, the type of product sold, the selling channels and price range. The overall evaluation has been positive. The most useful feedbacks that can be used to further improve the value proposition are the following:

- The configuration process was perceived simple and intuitive.
- Manufacturing and delivery time are acceptable up to 1 week.
- Sustainability aspects represent a plus for most of the customers.
- Hands-on production is perceived as an emotional experience.

5 Conclusions

Advances in information technology are one of the most promising enablers to effectively implement mass customization strategies. In this paper, the concept of "design to manufacturing in one step" has been explored and operationalized by developing a Gateway that provides a centralized software backbone for the operation of the whole mini-factory. A modular architecture enables an easy integration with any ERP and scheduling system making the system flexible enough to be deployed in different scenarios, even on existing infrastructures. The practical application of the developed IT infrastructure along with its performance has been tested by setting up a mini-factory in a shopping mall. Even if the demonstration scenario was a simplified one due to the temporary nature of the initiative, the integration of the software modules through the Gateway proved to be successful. Above all, the time and cost to get mass-customized products were in line with the expectations, thus confirming the ability of the IT infrastructure to support the offer of a mass-customized portfolio of products. As a further step, it would be advisable to extend the use of the IT infrastructure in different operative environments to fully test its potentialities. In particular, future works will be dedicated to the extension of the configuration environment to a web based application supporting the hosting on furniture marketplaces.

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Mass Customization 4.0 in AEC: Additive Manufacturing for Innovative Building Systems

Ingrid Paoletti

Abstract This paper highlights the possibility to realize innovative building systems, thanks to additive manufacturing, opening the way to mass customization in AEC. Two examples of building systems are described, from ACTLAB, ABC Dept., Politecnico di Milano, that have been designed, thanks to computational tools and innovative manufacturing techniques. The first one is a functionally graduated lattice structure; the second one is a complex mould. Both have been realized with FDM and polymeric materials in a very interesting design to fabrication process. Finally some 'what ifs' are traced for a wide diffusion of AM in AEC.

Keywords Innovative building technologies · Mass customization in AEC · Additive manufacturing

1 The New Conditions for Mass Customization 4.0 in AEC

Our planet is facing enormous problems nowadays, just to quote some: exponential increase of population, scarcity of resources, need of recycling due to high quantity of waste and overheating of the Earth.

An answer European Community is working on is 'circular economy' with the objective to ensure a new way of looking at the relationship between markets, customers and natural resources.

The circular economy moves away from the traditional 'take-make-dispose' economic model to one that is regenerative by design. The goal is to retain as much value as possible from resources, products, parts and materials to create a system that allows for long life, optimal reuse, refurbishment, remanufacturing and recycling (World Business Council for Sustainable Development, [8]).

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The last decades have been marked by a growing concern over scarcity of resources caused by the rapid industrialization of emerging economies as well as by the high material consumption at a global scale. The overconsumption of resources is contributing to one of the greatest challenges of twenty-first century. The amounts of material that is being extracted, harvested and consumed in the last decades are increasing tremendously and bringing the serious problem of resource scarcity. Coal, oil and gas are not only becoming increasingly scarce but are also accelerating emergence of sensitive global crisis leading to climate change and exceeded CO2 emissions. As all other responsible segments of society and professional groups, architects too are challenged to rethink the way of designing, building and confronting with materials. They are expected to make a crucial contribution to the ecological turnaround through the intelligent and forward-looking design, use of materials, technology, recycling requirements and energy use (Fig. 1).

These questions open also new horizons for industry to become more efficient, to improve processes and to develop innovative products and services to answer to those big themes.

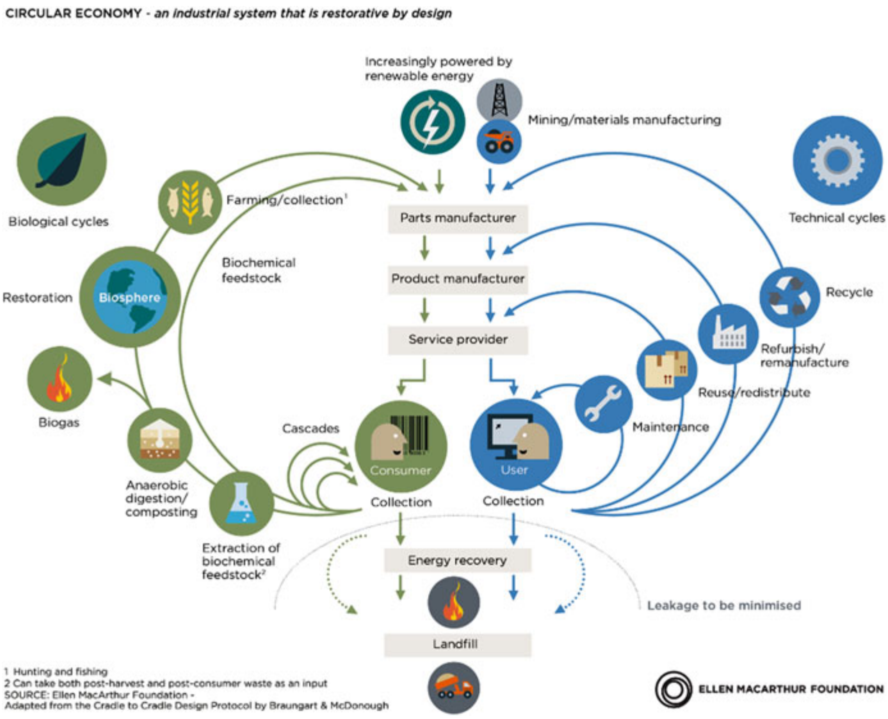

Fig. 1 Circular economy scheme

Globally there is a high awareness that industry stands on the brink of a new revolution, driven by technological breakthroughs such as advanced computing, big data analytics and cloud, advanced robotics and innovative manufacturing.

On this side the market is evolving, making very difficult to make previsions and responding to customers' demand for personalized products and services, safety and comfort as well as improved energy and resource efficiency.

Many researchers have already named it Industry 4.0, tackling it as the revolution that refers to the possibility to manufacture with a very high quantity of data (Schwab 2015).

European industry is strong in sectors such as electronics automotive, security and energy markets, manufacturing, robotics, telecom equipment, business software and laser and sensor technologies but seems sometimes to forget how these applications can be fostered to construction industry, which in reality has a lot of responsibility in society development.

On the other side, manufacturing techniques and innovative production methods in construction seem often quite resilient to change. This is due to traditional construction methods and consolidated process of production, where innovation is often a very slow process which is driven by economic reasons more than by effective need of new products or systems. However, emerging construction processes are more and more influenced by novel design methodologies that enable new ways of manufacturing. Among them, computational design, early-stage engineering, topology optimization and material distributions are the most significant ones [1].

In this context, mass customization (Pine 1983) refers to the possibility to evolve from already existing systems to the novel ones that can be personalized, without increasing their cost and causing the new technologies to emerge in this fast-changing scenario.

In architecture, engineering and construction (AEC) sector particularly, in order to meet requirements of nowadays performative and competing design-to-fabrication techniques, it is important to produce elements, components or overall integrated systems with highly specific customized characterization while keeping low its costs.

2 Innovation Drivers for AEC

Two of the most relevant drivers for innovation in construction industry are:

- Computational design
- Advanced manufacturing

Computational design is a contemporary technique that enhances overall design-to-fabrication processes by incorporating various materials and structural and geometrical data to compose, describe and inform architectural design and performances. This means that the process is no longer linear, assessing properties and performances when the design phase is over, but reiterative, where information are exchanged and connected to design from the very beginning.

Computational design can give at least three possibilities:

- To engineer a specific form from the early concept of the design process
- To customize tools for the materialization of a specific design
- To activate certain embedded properties of a material more than others as a main driver of performative design

Designers and all the operators along the AEC process are therefore able to combine and develop multiple tools and create geometrically complex structures, optimizing various parameters to control whether the inputs or the results. The knowledge of a proper coding language, such as Python, C# or Visual Basic, opens up a wide range of possibilities for scripting desired geometries and properties.

Advanced manufacturing refers to the possibility to tailor each computer numerically control (CNC) machine in order to fit in an appropriate way the design of each product, component or system. Nowadays, industry is moving very fast along this direction due to the fact that new machines have user-friendly tool to set them, are much for efficient in terms of time and quality and allow new types of work that can improve products.

Advanced manufacturing refers often to ICT but has also its centre core in the possibility to transfer in a fast and effective way the experimental researches coming from innovative discovery or application into manufacturing process or products.

The industrial culture to refer to nowadays is therefore deeply embedded to advancement in software skills and machine capability increasing designers' and producers' possibility to develop innovative technologies also for AEC with the, namely, fourth industrial revolution.

3 Experimentation on Design for Fabrication with Additive Manufacturing

Design for fabrication is typical of a lot of sectors, but is not so diffused for AEC due to different reasons: Euclidean geometry rules, regulations, lack of competences on computational design and multi-material building systems.

The generally accepted model of the design process is as something which outputs a solution based on given requirements, different for each industry, in a linear process [4]. Today however a new experimental line of research is pushing towards the design of customized building components with computational techniques and advanced manufacturing, in order to respond to the changing scenario. In particular one of the manufacturing techniques which have gained success in the last year is additive manufacturing, due to the possibility to customize shape and material in a very accessible way.

Two case studies will be described in this paper where additive manufacturing has been used to develop innovative building systems with customized design and performances. The first one is a lattice structure designed with topological optimization in order to exploit the possibilities of making lightweight structures with an efficient weight-to-strength ratio and with a complete mass customized design. The second one is a mould design for complex casting where particular shapes are required.

Both these experimentations have been run at ACTLAB, ABC Dept., Politecnico di Milano, a research unit which explores new possibility of design of building systems.

The manufacturing technique employed is fused deposition modelling (FDM), which is one of the possible technologies that can be used for additive manufacturing. Fused deposition modelling (FDM) is an additive manufacturing technology that builds parts up layer by layer by heating and extruding thermoplastic filament. FDM is in principle applicable to any thermoplastic, thus allowing the use of materials with outstanding thermal and chemical resistance and excellent strength-to-weight ratios. It is based on the extrusion of a material that has been heated up to reach a semi-solid state and is thus able to be reshaped into the desired form. Currently, it is considered as the AM method that best satisfies speed, cost-effectiveness and dimensional accuracy.

The material employed is a polymeric material, which is one of the most evolving materials in general, due to its customizable properties and low cost of production. Fused deposition modelling (FDM) of thermoplastic polymers is further enhancing this approach since the thermoplastic polymers have a very important embedded property: they can be modelled into desired shape while preserving most of their mechanical and thermal properties. While this might not be an active property, it is considered as a fundamental asset that is at the core of the versatility of the FDM process. The FDM is therefore a synthetic material system, in which matter distribution and organization arise as mediation between the designer and computational logics.

3.1 Functionally Graded Lattice Structures

The first experimental construction system is a building component with highly specific material distribution which has been conceived with the use of AM to efficiently provide structural resistance, with a method that encompasses computational design workflow, fabrication experiments and performative assessment of full-scale prototypes.

Algorithms for topology optimization of free-form shapes are employed to determine the material organization as well as a performative matrix for the creation of a custom lattice microstructure defined as functionally graded lattice structures, a system of load-responsive interconnected struts with spatially varying characteristics.

The potential of this system relies on its implicit resistance and reduced use of material, combined with the possibility to adapt to any architectural shape. Lattice microstructures are considered both as a structure and as a material. They are composed by an interconnected network of struts, pin-jointed or rigidly bonded at their connections. At one level, they can be analysed using classical methods of mechanics, as typical space frames. On the other side, within a certain scale range, lattice can be considered as a material, with its own set of effective properties, allowing direct comparison with homogeneous materials. Mechanical properties of lattice materials are governed, in part, by those of the material from which they are made, but most importantly by the topology and relative density of the cellular structure.

This methodology requires the description of custom algorithms to generate lattice structures parametrized on the base of a continuous feedback loop from a topology optimization and manage the additive process of materialization.

The outcome of this analysis is then directly translated into a lattice microstructure which orients itself following principal stress lines and varying material porosity, according to local stress values. In this process, main input parameters are material properties and fabrication constraints of AM, overall geometry and boundary conditions.

Variations in any of these parameters generate different lattice structures, as this research develops a global method for highly specific design, where morphological, material and performative information is read, analysed and modified iteratively.

The efficiency of functionally graded lattice structures relies on highly specific complex geometries. In this research, AM is employed to manage high intricacy and resolution, while offering the potential of experimenting with different materials, which in turn can become new inputs to the structural definition. Typically, AM methods produce objects in a sequence of horizontal layers. This allows great freedom in production but also some constraints to be taken into account. Overhanging geometries are difficult to print and, according to the material used and the printing resolution required, have to be limited to an angle of 30–45° from the vertical axis. Various production tests have been conducted to refine print settings with different materials and to define strut geometries and dimensions in relation to print speed and resolution. Octahedron cells have proven to be ideal to guarantee a streamlined production while offering a degree of freedom allowing variable mechanical and visual features [6].

An innovative building component has been fabricated to evaluate stiffness, lightness and permeability at full scale according to variation in porosity (relative density) [2].

Larger samples of cellular structures have been manufactured inscribed within a 500-mm-wide cuboid component. Interestingly, same (or close enough) relative density can be reached with different cell sizes and very different visual perceptions. Various configurations have been considered seeking for the geometrical limits and constraints of the lattice structure considering relationship between the cell size, strut thickness and cell angle.

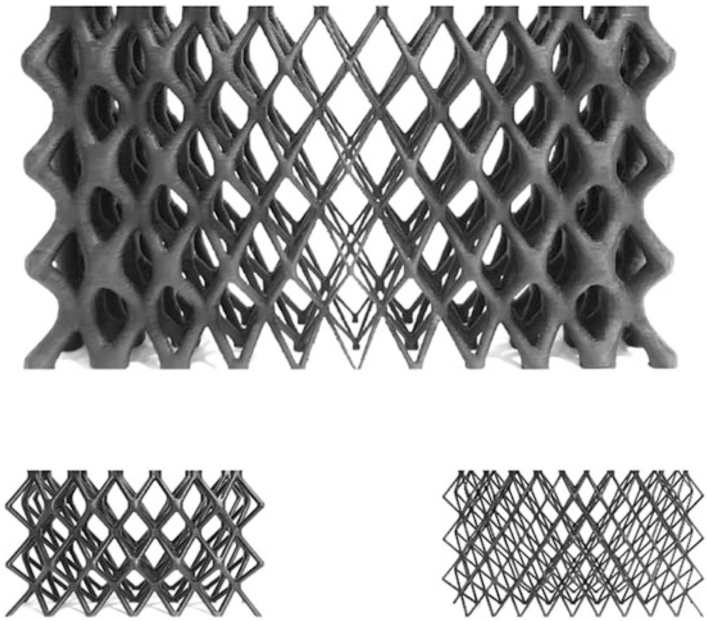

Fig. 2 Functionally graded lattice structures realized with additive manufacturing. Prototypical components 500 mm wide with different relative density: from left – $\rho = 0.04$, $\rho = 0.05$, $\rho = (0.04$ to $0.06)$

The quality on the bonding between the layers depends both on the geometry and on the printing parameters, most importantly the extrusion temperature. The thermal energy allows the growth of the neck formed between the two layers as well as the molecular diffusion and randomization of the polymer chains across it (Sun et al. 2008) (Fig. 2).

Finite element analysis and physical printed part testing show that printed materials have higher tensile, compressive and bending stresses than their isotropic counterparts, along the extrusion direction.

The lattice brick with basic cells, weighing 220 g, stands the applied load of 3000 N (300 kg), and reinforced one (with inclusion of the vertical strut) performed even three times better, resisting the load of 10,000 N (1000 kg) (Fig. 3).

The overall design to fabrication process is defined and controlled through the algorithmic programming. A G-code is generated through Grasshopper and sent directly to the printers which enables for a highly precise control over the material use and organization within each component. The fabrication process involves a *printing farm* of five industrial printers that are producing approximately seven components per day, printing at a speed of 60 mm/s in order to not compromise the quality and precision (Fig. 4).

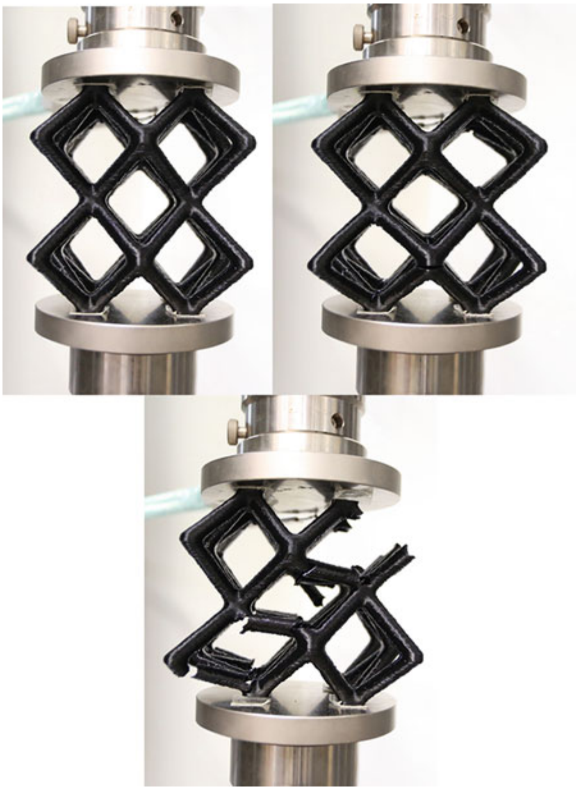

Fig. 3 Compression testing of the lattice bricks

Fig. 4 Additive manufacturing printing farm at Politecnico di Milano University

3.2 Additive Moulding for Complex Casting

This experimentation relies on the gap between the integration of AM into the realization of complex moulds and the casting of interesting customized concrete structures.

Many of the available construction methods are not capable of manufacturing complex geometric shapes in the scale of buildings. As a consequence, many complex geometries are produced with little success with traditional tools such as milling, turning and casting. Usually CNC milling is employed for component making purposes, but it is quite limited in the sense of creating shapes that are freely formed, therefore highly complex.

Even if complex shapes seem to move away from a constructive approach, the structural complexity, together with morphological language, and specific performances arise new requirements, stimulating innovation [3].

Usually moulds are a very important and though part of the construction process of concrete components, but they also influence the design, simplifying shapes due to economically unfeasibility, partially as a result of the increased labour and formwork costs, partially related to the request of mass produced pieces [8].

The suggested innovative building system is composed by mould making via AM and a bonding method allowing the moulds to be connected uninterruptedly. The resulting continuous mould is obtained by assembling components and permits monolithic casting for large concrete elements in an economic process.

The chosen forms for the experiments are results of parametric definitions advanced with computational tools, and initial formworks are designed in a very small scale, so the casting is made only with sand, cement and water since the formwork is highly deformable and delicate when it is subject to loads. The design is a perforated column with the intention to push the complexity in order to justify the use of AM for a mould with a twisted shape (Fig. 5).

Different trials in shape and material have been conducted in order to find the correct mixture, and the final prototype has been designed in order to combine geometric complexity, a particular curvature that could be only realized with AM and finally a surface characterization.

The surface characterization was studied in order to increase designer's flexibility and to achieve an external finishing that doesn't need post-manufacturing work to reach the stage of final product (Fig. 6).

This new methodology of mould fabrication can open a mass customized design of building systems that can foster also a new industrialized production method in a small scale, altering the contemporary concrete casting practice.

Fig. 5 Moulds for additive manufactured twisted columns

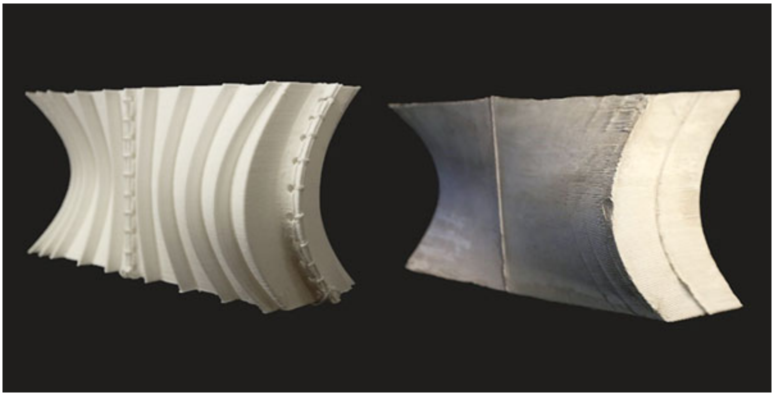

Fig. 6 Example of concrete moulding with particular curvature and surface

4 What If: Conditions for a Wide Diffusion of Mass Customization with AM in AEC

The two case studies suggest that in order to enhance AM in AEC, different factors have to be undertaken:

- Type of material with its embedded properties, in order to maximize its use in a specific building component in relation to mechanical properties and performances required
- Printing settings in relation to geometric constraints
- Geometric constraints in terms of cell definition, angle inclination, size and strut thicknesses
- Printing time and resolution

If we should analyse the 'what if' condition for the wide diffusion of mass customization with additive manufacturing in AEC, at least these conditions should happen:

- Reduction of time needed using AM techniques
- Regulation standards for the introduction of these types of customized products in EU market and other markets
- Rise of competence in the AEC sector to deal with innovative design to fabrication process

In conclusion it is visible and clear how mass customization is reaching a maturity phase due to advancement in computational and manufacturing techniques which are fostering an innovative way of design thinking much more 'informed' than before [5]. The amount of information a designer can handle will develop a new approach to fabrication of building systems that will allow also the introduction of breakthrough innovations, usually not typical of AEC.

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Managing Customized and Profitable Product Portfolios Using Advanced Analytics

Günther Schuh, Michael Riesener, and Merle-Hendrikje Jank

Abstract Due to heterogeneous and volatile customer requirements as well as a growing demand for individualized products, companies nowadays face a highly uncertain environment. As a consequence, the number of product variants offered has increased drastically in recent years and across all industries. That way, the complexity of the product portfolio increased, too. Due to this complexity, internal costs rise and often outweigh possible sales revenues. Under these circumstances, to satisfy various customer requirements and to keep profitability high, a dynamic optimization of the product portfolio is necessary. Existing literature discusses the topic of configuration management for product portfolios regarding diverse circumstances. While current research focuses on the tracking of costs related to configuration changes either while they occur or retrospectively, no approach succeeds in cost and demand prediction. In this paper, the topics of product portfolio management and advanced analytics are combined to overcome the limitation of retrospective modeling. A concept for a methodology to dynamically optimize the product portfolio during the use phase is suggested. Moreover, the methodology aims at predicting the optimal portfolio configuration using real-time data and advanced analytics. That way, customized and profitable product portfolios are realized efficiently.

Keywords Product portfolio management · Advanced analytics · Customization · Dynamic control · Portfolio profitability

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1 Introduction

In recent years, the number of sales markets being dominated by customers increased rapidly [1]. Thus, while mass production was sufficient to fulfill customer expectations for many years, companies nowadays are facing customer heterogeneities and a growing demand for individualized products [2]. To satisfy customer requirements and to withstand international competition, companies across all industries introduce new products and product variants into their portfolio. As a result of the growing portfolio complexity, internal processes become more complex as well. Since companies often disregard low sales quantities when launching new product variants, complexity costs often outweigh possible sales revenues and lead to competitive disadvantages [3–6]. To prevent the latter from happening, it is necessary to manage product portfolios efficiently so that customer requirements are satisfied and profitability is kept high. However, the identification of product variants which are both demanded by customers and profitable for the company is rather challenging. Focusing on the identification of profitable product variants, the allocation of complexity costs is a promising method [3]. In contrast, to identify product variants that are highly demanded by customers, a product configurator is a helpful tool to interact with customers, generate data about customer preferences, and select sought-after product variants [7].

For a company to remain competitive, it is crucial to partition customer demands and offer customized products at profitable prices. While customer needs have been identified using interviews and product trials in recent decades, the heterogeneity of customer requirements and shorter product life cycles complicate product portfolio management. As a result, new methods for portfolio management are necessary. A possible enabler for the development of new methods are recent advances within the fields of information technology and data collection in particular. That way, comprehensive data sets about customer requirements become available.

Combining the fields of product portfolio management and data analytics, this paper promotes a concept for a methodology to dynamically optimize product portfolios using advanced analytics. Applying real-time user data, the product portfolio of a company can be continuously adapted to current customer demands and market needs. The portfolio adaption is done by complementing the scopes of products within the portfolio based on customer analyses and industry-specific requirements. In order to optimize the product portfolio for customization and profitability, each possible change in the portfolio configuration is validated, balancing the cost-revenue ratio.

The remainder of this article is organized as follows: In Sect. 2 the relevant terminology used in this article is defined to ensure a common understanding. Section 3 provides an overview of relevant work in the areas of product portfolio management and advanced analytics and identifies the research gap. Section 4 introduces the methodology for a dynamic optimization of profitable and customized product portfolios. The conclusion and future work steps can be found in Sect. 5.

2 Relevant Terminology

In order to achieve a consistent understanding about the relevant terminology used in this paper, the following sections describe the main concepts applied.

2.1 *Product Portfolio Management*

Product Portfolio In reference to Seeger, this paper defines a product portfolio as all services and products offered by a company [8]. As illustrated in Fig. 1, a product portfolio can be described by the help of the two dimensions: “portfolio width” and “portfolio depth” [8]. While portfolio width includes all different and coexisting product groups, the variety of product variants is depicted in the portfolio depth. The entirety of product variants in a portfolio at a certain time is called a product portfolio configuration.

Product Configurator Within the scope of this paper, product configurators are an important tool to support product portfolio management: In order to connect market demands, represented by customer requirements, and technical possibilities, a product configurator is used. In this regard, a product configurator is not only necessary to depict realistic product variants, but the configuration process itself is the key process to enable product customization. In general, the configuration process can be generalized into three steps [9]:

- Identification of relevant product components
- Analysis of component dependencies
- Comparison of customer requirements and configured product

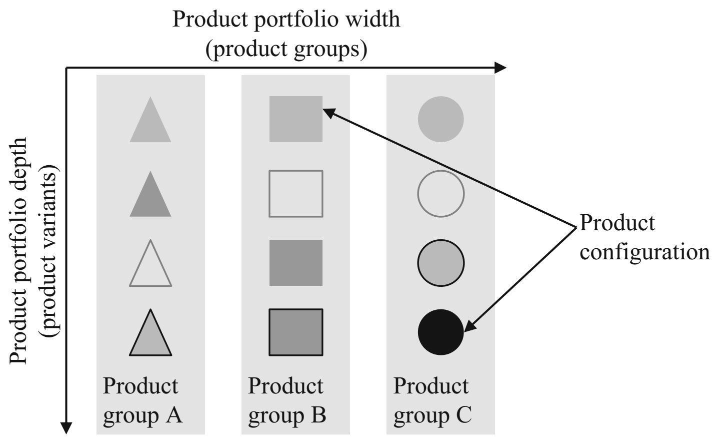

Fig. 1 Illustration of product portfolio

Additionally, product configurators are especially relevant for portfolio management, as the configuration process itself is a source of valuable customer data. Configurators distinguish themselves based on the underlying configuration logic [7]; see also Sect. 3.1.

2.2 Advanced Analytics for Demand and Profitability Predictions

Advanced Analytics The term "advanced analytics" is not clearly described in literature. However, it refers to a bundle of superior data mining processes by which current and historic data can be analyzed efficiently [10]. That way, statistical predictions about the future can be drawn. With the help of advanced analytics, structured (e.g., data in tables), semi-structured (e.g., graphs), and unstructured data (e.g., texts or images) can be analyzed. This is done using sophisticated quantitative methods such as statistical and predictive data mining as well as simulation and optimization techniques. Advanced analytics is superior to commonly known business intelligence approaches, such as reporting and query [11]. While there is no specific level of sophistication suggested in literature for methods to be called "advanced," predictive and prescriptive analytics are often termed as processes by which "advanced analytics" is performed [10]. Figure 2 provides an overview of common data mining techniques.

Using advanced analytics in business, companies are capable of detecting unknown risks and opportunities based on an iterative and continuous data analysis

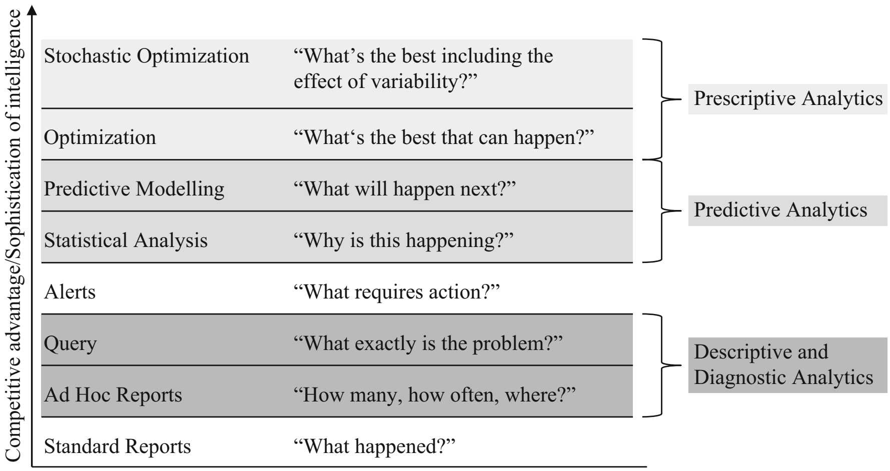

Fig. 2 Overview of different data mining processes and classification of predictive and prescriptive analytics as representatives for advanced analytics. (Adapted from Davenport and Harris [12])

[13]. Also, it is possible to understand customer requirements by the help of advanced analytics and to anticipate actions for demand satisfaction. That way, data is used as a strategic element for radical product personalization and profit maximization [13]. Product and pricing decisions can also be optimized using advanced analytic techniques [14].

Referring to Fig. 2, predictive and prescriptive analytics are especially relevant within the scope of this paper and are therefore described in detail in the following sections.

Predictive and Prescriptive Analytics Predictive analytics cover a portfolio of computer-aided statistics, machine learning, and data mining [11]. With the help of predictive models, historic and current data is analyzed to draw accurate predictions about the future. While predictive analytics is only capable of anticipating the future, these methods do not provide any guidance suggestions. In contrast, prescriptive models are successful in both modeling what the future will be like and giving guidance for the current situation. That way, today's behavior can facilitate or prevent events that are likely to happen in the future. By visualizing how future events will impact a company, businesses can, for instance, proactively build up a future portfolio strategy. Thus, as shown in Fig. 2, methods that belong to the group of predictive and prescriptive data mining methodologies provide the highest competitive advantage for the user.

Availability of Data The availability of data is key for designing predictive and prescriptive models. Hereby, not only a certain quantity of data must be available for modeling, but the available data must also provide attributes that characterize customers and their product preferences.

Based on the quantity of available data, different data types are characterized. "Big data" refers to a large amount of unstructured data regarding customer behavior and product portfolio configurations. Thus, to extract knowledge from the unstructured data sets generated, data mining approaches are needed [15]. In case there are fewer data points available than the number of parameters to be predicted, the term "scarce data" is used. Additionally, "censored data" occurs if the data itself is influenced by the optimization of the product portfolio itself.

Based on the quality of available data, three data types are distinguished. The least preferable type is characterized by data solely collected for product purchases, while there is no systematic record of the product portfolio configuration at the time purchases took place. That way, it is difficult to make assumptions about customer demand. The second type, "clickstream data," includes not only data about purchases and product portfolio configurations, but a thorough data set about customers' behavior is collected. Alternative items, which the customer was tempted to buy, are included in "clickstream data" as well. The most significant information can be extracted from "panel data" sets. These sets provide data for each individual customer, his demands and behavior over several periods. Analyzing "panel data" allows for an analysis of the relation between customer and provider enabling a more thorough understanding of customers' demand so that the product portfolio can be easily optimized for profitability and customer value.

For the methodology proposed in this study, it is important to have a sufficient data quality and quantity available to optimize portfolio profitability. A large quantity of “panel data” is the most preferred data set.

3 Related Work

The paper at hand promotes a methodology to dynamically adapt and optimize product portfolios using advanced analytics. To identify a research gap, this section evaluates state-of-the-art research within the topics of product portfolio management, advanced analytics, and knowledge discovery methodologies.

3.1 Product Portfolio Management

A product configurator, serving as mediator between customer requirements and the technical possibilities, should only consider product variants that are relevant to customers and technically feasible. Based on this, Blecker et al. identify the database of the product configurator as one of the most important criteria for configurator distinction [7]. Categorized by the database, “rule-based,” “model-based,” and “case-specific” configurators are distinguished [7]. A rule-based product configurator uses an “if-then” logic, starting from a condition and deriving a consequence. Due to the fact that all conditions and consequences have to be known prior to configuration, the costs for building an initial database are high.

A model-based configurator is specified by the way the model is set up. Regarding this, three different model setups are distinguished within model-based configurators: logic-based, resource-based, and constraint-based. Within a logical model-based configurator, objects, concepts, and binary relations are connected logically. A resource-based configurator aims at connecting manufacturer and customers within the configuration, whereby all elements are described by attributes which specify what resources are contributed, used, or consumed [7].

In contrast to the previous configurators, a case-specific configuration logic does not need a complete database as input. Based on a library of diverse cases, a new configuration task is compared to all library entries to find the most similar case. As it is unlikely to have two perfectly identical cases, only minor adjustments between the two cases have to be made [16].

The previously described existing configurator setups are a reliable basis for the methodology to be promoted in this paper. However, the configurators in need of complete databases are not suitable to validate the launch of a new product variant. The only configurator logic which is not restricted to a complete database, the case-based configurator, only allows for similarity evaluation but neglects possible cost-profitability aspects [17].

Seifert et al. use an infinite-horizon Markov decision process to dynamically optimize product portfolios considering product life cycles [18]. The authors focus on the timing of product launches, marketing, and inventory decisions, given a certain amount of working capital as constraint. While the method is successful in demonstrating that the joint management increases total profit, it does not consider both portfolio configuration aspects and customer demand. In contrast, Rebentisch et al. propose a methodology to optimize product portfolios regarding customer value, thus dealing with the number of product variants efficiently [19]. With the help of five attributes, such as product quality and innovation capacity, the methodology measures changes in customer value as a function of the number of product variants offered and the attributes used. However, the methodology only focuses on customer value, disregarding profitability aspects. Moreover, the methodology is limited to a retrospective portfolio adaption and B2B companies. In order to extract customer feedback, Li et al. developed a social intelligence mechanism that is capable of translating customer reviews into insights about product feature specification and importance [20]. The knowledge gained should support companies to develop the next product generation which satisfies customer expectations. Although the proposed methodology is successful in measuring product feature significance to customers, it does not consider product portfolio configuration aspects to translate customer expectations in possible product variants.

In conclusion, several methodologies which focus on product portfolio management regarding diverse circumstances are available. Costs induced by portfolio changes can be recorded retrospectively or along the development process. Also, product portfolio customization is targeted within current research proposals by focusing on customer value creating and portfolio optimization based on feature extraction from social media platforms. However, none of the presented methodologies are capable of combining the topics of data mining and product portfolio management so that a proactive, dynamic configuration and customization of product portfolios is possible.

3.2 Advanced Analytics

As stated by Liberatore and Luo, the idea of "advanced analytics" extends commonly known operations research methodologies using data-driven predictive and prescriptive methods to support decision-making processes quantitatively [21]. Within the scope of this paper, only studies that apply methodologies of advanced analytics to optimize profit are addressed.

Profit optimization using advanced analytics is especially common within the transport industry. In this context, Agatz et al. combine predictive methods and cost optimization using the problem of fulfillment of demand within supply chains [22]. An extensive review about research regarding the fulfillment of demand with respect to revenue management is provided by Cleophas et al. [23]. According to Talluri et al., revenue maximization is the result of solving a stochastic model using dynamic programming [24]. However, due to the high number of consecutive decisions, only heuristic approaches can be solved considering limited computational resources.

The widely known Expected Marginal Seat Revenue (EMSR) heuristic by Belobaba addresses the problem of revenue management: Based on customer demand, EMSR calculates the number of products to be sold within a certain value category and allocates production resources accordingly. The adaption of the portfolio is not in the scope of this work. Among others, Kunnumkal [25] and Meissner [26] propose column generation and approximative dynamic programs for product portfolio adaption with respect to product dependencies. As described by Cheraghi et al., with the help of revenue management approaches, it is possible to maximize revenue by allocating a company's resources to different customers at different prices [27]. While Cheraphi et al. provide a thorough literature review regarding revenue management in the service and manufacturing sector, product portfolio characteristics are not considered.

Moreover, based on the increasing amount of available customer data sets, nonparametric methodologies to describe customer demand preferences as well as panel data are becoming increasingly important [28]. As customers define their preferences based on alternatively available products and over several time intervals, the application of nonparametric methodologies is crucial [29]. Using nonparametric applications, functions describing customer preferences are set up based on data and are not bound to previously designed static models.

In conclusion, diverse methods for profit optimization using predictive analytics within the service business have been found. However, none of the methods presented are capable of proactively optimizing complex product portfolios as not all relevant portfolio characteristics are covered. Also, available studies focus on predictive methods and omit prescriptive ones. The latter must also be developed to provide guidance in the portfolio adaption process. The paper at hand addresses this research gap.

3.3 Knowledge Discovery Methodologies

After presenting related work in the fields of product portfolio management and advanced analytics, this paragraph focuses on methodologies, i.e., processes and models, to extract knowledge from data.

The knowledge discovery in databases process (KDD process) is defined by Fayyad et al. as "the nontrivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data" [30]. Thus, this process is used to transform data into useful knowledge. Often, KDD and data mining are used as synonyms [31, 32]. However, while KDD refers to the overall process of discovering knowledge, data mining is identified to be a particular step in the KDD process [30]. As described by Fayyad et al., the data mining process step makes use of algorithms to extract patterns from data. The overall KDD process can be summarized in nine process steps, including the data mining step (see [31] for further details). These steps are executed in an iterative order, whereas the number of loops between any two steps is not specified by the authors [31].

As the KDD process was mainly established for academic purpose, industrial models were set up to adapt the process steps to industrial applications. Among others the six-step industrial cross-industry standard process for data mining (CRISP-DM) model was established in 1997 by an industry group [31]. As described by Zanin et al., this process consists of the following steps: business understanding, data understanding, data preparation, modeling, evaluation, and deployment [32]. The paper at hand makes use of these standard knowledge discovery processes and aims at both specifying and extending existing knowledge discovery processes to manage profitable product portfolios.

4 Methodology Design

After presenting relevant terminology and latest studies within the topic of product portfolio management and advanced analytics in Sects. 2 and 3, this section aims at proposing the concept of a methodology that optimizes product portfolios using advanced analytics. The methodology focuses on portfolio adaption during the use phase of the product portfolio and seeks to enhance customer satisfaction and customer involvement using real-time data evaluation.

4.1 The Model Derivation Process

According to Schuh et al. [33], an advanced analytics model can be set up by the following six steps: “target definition,” “data selection,” “methodology selection,” “methodology implementation,” “methodology evaluation,” and “prediction” (see Fig. 3). All six process steps are arranged in a consecutive order, although it can be necessary to iterate back to the “methodology selection” process step if the methodology has been evaluated to be insufficient. These six process steps can be divided into two phases “development” and “evaluation/application.” Within the scope of this paper, the focus is put on the first two process steps, “target definition” and “data selection.” The third step, “methodology selection,” is slightly addressed as well. However, “method implementation” and the “evaluation/application” phase are out of the project scope as it is depicted in Fig. 3.

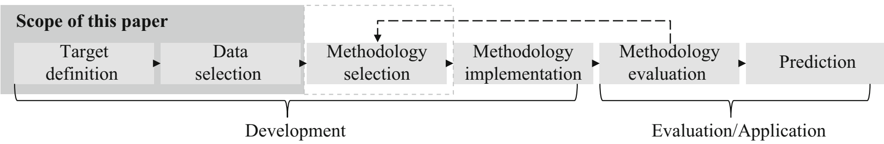

Fig. 3 Process to derive an advanced analytics model [33]. The process step “methodology selection” is depicted in a dashed frame as it is only roughly addressed in this paper

Step 1: Target Definition In order to develop an advanced analytics model, it is crucial to define the target of the model at first. The main target of a company is to increase profitability. According to Tolonen et al., the targets of a successful product portfolio management are aligned with the company's targets [29]. Thus, profitability is the overarching target for portfolio management and, consequently, also for the model to be developed.

In general, profitability is mainly influenced by both costs and demand. While there is a positive relationship between profit and demand, an increase in costs reduces profitability. Regarding this, to set up an advanced analytics model that optimizes product portfolio profitability, it is necessary to quantify demand (i.e., customer demand) and costs (i.e., direct costs and complexity costs).

Step 2: Data Selection For cost and demand quantification, respective data sets need to be selected. These data sets will be used for designing and training the advanced analytics methodology. Only if the advanced analytics model can be trained with reasonable data sets, both predictions and prescriptions are most likely to depict the future. Regarding product portfolio profitability, five main profitability drivers have been initially identified (see Fig. 4): "customer satisfaction," "market position of products," "efficiency in product configuration and manufacturing process," "product costs," and "degree of product standardization." Within the scope of this paper, the term "driver" is applied for facts or conditions whose changes affect the model target. Thus, by altering one of these five drivers, the portfolio profitability will be influenced as well. However, it is challenging to quantify these

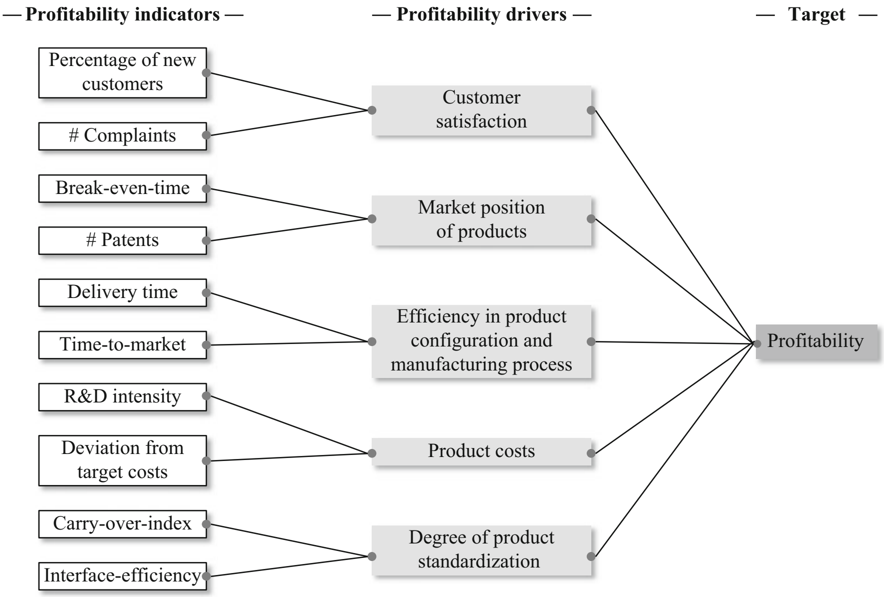

Fig. 4 Data selection: second step of the derivation process for an advanced analytics model

drivers by means of data. Therefore, the drivers have been narrowed down to specific indicators. In contrast to drivers, indicators can be measured using scales and statistics, for instance. As shown in Fig. 4, ten major indicators were identified after extensive literature studies [34–37]. Customer satisfaction, for instance, is one of the key drivers for the profitability of a product portfolio. To quantify the influence of a driver on a target, performance indicators are defined and measured using scales, for instance. To quantify "customer satisfaction," for instance, data sets about the number of customer complaints as well as the percentage of new customers can be collected. In this regard, product configurators are an important enabler for the methodology to be developed, as data sets are collected when customers configure products.

Step 3: Methodology Selection After selecting appropriate data sets, a methodology must be chosen that is capable of handling the selected data sets (i.e., the profitability indicators). The selection process itself is beyond the scope of this article. However, an adequate methodology that is successful in dynamically predicting profitability and customer value of product portfolios must be capable of:

- Predicting demand and revenue of product variants
- Predicting costs of product variants

In addition, for a dynamic optimization of portfolio profitability and customer value, the method must be prescriptive. That way, based on the results of demand and cost prediction, the method serves as decision-making support tool and recommends necessary actions so that the predicted outcome can be realized. Regarding this, artificial neural networks are a promising method as they provide those crucial characteristics. An extensive review about the characteristics of artificial neural networks is found in Basheer and Hajmeer [38].

Following the model derivation process, the relevant methodologies (e.g., neural networks) must be implemented and evaluated.

5 Conclusion and Future Work

Due to customer heterogeneities and a growing demand for individualized products, companies nowadays face a highly uncertain environment. Companies are tempted to satisfy individual customer requirements by offering more product variants regardless of low sales quantities. That way, the number of product variants offered and product complexity increased drastically in recent years. However, not only product portfolio complexity increased but also complexity costs rose disproportionally. As a consequence, rising complexity costs often outweigh possible sales revenues and lead to competitive disadvantages. To prevent the latter from happening, the article at hand introduces a concept for a methodology that applies advanced analytics to dynamically manage product portfolios during its use phase. The overall aim is to satisfy customer requirements and keep profitability high.

The model design process applied in this work includes a development and evaluation phase, but up to this point, research is limited to the development phase. Within the first step of the design process, the model target needs to be defined. In general, the strategic goal of a company is to create customer value and increase profitability. As the target of a successful product portfolio management is aligned with the strategic company target, portfolio management is also aiming at optimizing profitability. Thus, when setting up a model for portfolio management, the overarching target of the model is to optimize portfolio profitability.

After target definition, the model deviation process focuses on data selection. It is found that profitability is influenced by a set of five main profitability drivers, such as customer satisfaction and product costs. In order to quantify those drivers, profitability indicators are identified. For those indicators, data sets can be selected and imported in the model to be designed. Having selected adequate data sets for model derivation, a specific advanced analytics methodology has to be chosen. This work closes with a suggestion of artificial neural networks as a promising methodology for portfolio optimization purposes.

This work is successful in providing a model concept for a dynamic optimization of product portfolios regarding customization and profitability. Future research should focus on the selection of an appropriate advanced analytics methodology for model setup, implementation, and evaluation. In this regard, the identification of industry-specific product portfolio parameters and customer demands is crucial for model setup. For evaluation purposes, not only data sets but also expert interviews could be used.

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Impacts of Industry 4.0 on the Specific Case of Mass Customization Through Modeling and Simulation Approach

Ali Raza, Lobna Haouari, Margherita Pero, and Nabil Absi

Abstract Since the last decades, companies have been increasing product variety, thus forcing manufacturers to create more and more customized products. To manage such contexts, manufacturing companies are adopting mass customization, i.e., a manufacturing strategy that aims to offer customized goods at low cost. Recently, advancements in information system technologies provide new opportunities for the manufacturing sector. In particular, the concept of Industry 4.0, i.e., the application of the concepts of smartness and networking to the manufacturing environment, is providing tools to reduce the complexity of managing production systems. Despite the relevance of both areas, how mass customization can be integrated with Industry 4.0 concept and what are the benefits of such an integration are still open issues. Therefore, this study investigates how to implement the Industry 4.0 concept for the specific case of mass customization industry and, by using modeling and simulation, proposes a quantification of the benefits of such implementation. Implementing Industry 4.0 solutions requires high level of investments, and there is a great need of research that outlines its quantifiable benefits to justify the investments. To the aim of the research, two conceptual models, one integrating Industry 4.0 and mass customization and one featuring only mass customization, have been developed. Afterward, these two models have been simulated in FlexSim software in order to measure the performance. The results obtained seem to be extremely favorable for the implementation of Industry 4.0 solutions on mass customization systems. Significant improvement in product completion rate on time, customer satisfaction rate, utilization of equipment, and waiting time in queues has been observed. This

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study will help mass customization industries to understand the opportunities and criticalities concerned with the implementation of this concept.

Keywords Mass customization · Industry 4.0 · Simulation · Future mass customization industries

1 Introduction

In the last decades, competition between manufacturers gradually became tough, mainly due to globalization [1]. The demand for greater product variety used to increase greatly due to diverse customer needs and use. This context puts manufacturers under the increasing pressure to provide products that meet the requirements of individual customers [2]. To deal with this new industrial situation, manufacturers offer more and more customized products to customers. This resulted in the so-called mass customization systems [3]. The concept of mass customization (MC) was first introduced by Davis [4] in 1987 as the ability to supply services or products to match with individual customer specifications through great flexibility and integration. A concrete definition of mass-customized production given by Modrak [5] says that the products are made by flexible assembly processes consisting of several different modules. Modules or sub-modules are created from initial components. At the last station, an operator assembles components or modules into the final product.

Mass customization systems have several characteristics that differentiate them from the mass standardization systems. According to Heinz Gaub [6], the complexity of these systems is increasing incredibly that makes it difficult to operate in the competitive situations. On the other hand, customers are seeking for flexible solutions and tends to increase variant diversity and ever smaller lot sizes.

Also, in mass customization systems, customers wait during processing or assembly of their orders, unlike in make-to-stock systems. Therefore, cycle time should be as short as possible. The need of customer involvement in all the product development phases is getting more important for mass customization industry.

In parallel, latest advancements in information technology (IT) can play crucial role with the urgent need for tools that support the complexity of MC systems. In the last decade, various tools (i.e., RFID, barcode, etc.) have been implemented to increase efficiency of these systems, but there is always a gap for further improvements. Advancements in IT provide new opportunities to add value in the manufacturing sector. Adopting future manufacturing systems forces the industry to change the way it operates and its business model and concept. For instance, present-day enterprise resource planning (ERP) solutions needed manual operators to enter the data related to production and processes. The widespread adoption of information and communication technology by manufacturing industry and traditional production systems is diminishing the boundaries between the real and virtual world [7], and these are known as cyber-physical production systems (CPS).

Moreover, with the help of the Internet, a great variety of manufacturing "Things" and "Services" can be connected to create the "Things" and "Services" Internet, i.e., Internet of Things(IoT) and Internet of Services (IoS). All these transformations mark the transition of current industrial production to the fourth stage (i.e., Industry 4.0) which is characterized by smartness and networking.

The aim of this research work is to investigate how to implement the concept of Industry 4.0 into the mass customization systems and what are the benefits associated with such an integration. We used the simulation and modeling approach in our work. We modeled mass customization environment with the concept of Industry 4.0 and compared it with current mass customization environment of our industry in a simulation software named FlexSim. We measured the performance of both models to compare them and obtain some tangible results.

1.1 Problem Description

The importance to consider customer needs is increasing greatly, and it is becoming a vital source of existence for the companies if they want to survive in highly fluctuating industrial environment. This leads to more and more customized products as per specific customer needs. It involves big information and material flows that make the system more complex and results in decreasing the efficiency of the system. The latest IT developments hold a great potential to transform our current industry sector into a new level and increase the efficiency and performance of manufacturing systems, but the biggest barrier in the implementation of this concept is the huge amount of financial resources and risk. Therefore, there is a great need to provide some actual results on this concept to facilitate implementation of Industry 4.0. Simulation and modeling is considered as a great source to study the impacts of conceptual models that are difficult to implement practically because of limited resources and financial constraints. Also, it is extremely difficult to apply the concept of Industry 4.0 in all types of industries so we decided to implement it on a specific case of MC industries.

Our motivation is to develop a generalized simulation model that contains the basic characteristics of all mass-customized industries. The results for this model can be applied to all MC industry. However, if we go in more depth, results may vary slightly from case to case.

2 Research Questions

In order to investigate how to integrate MC and Industry 4.0 and what are the benefits of such integration, three research questions (RQs) have been formulated.

Firstly, it is required to find the characteristics of future mass customization industries and how the concept of the Industry 4.0 can best fit into mass customization environment. That leads us to formulate our first RQ. i.e.:

RQ 1: How can the concept of Industry 4.0 be implemented on the mass customization model?
Answering this RQ will lead us to define the pillars upon which we can base our conceptual model. After having a clear idea of the implementation of this concept on MC model, it is required to see how it will impact the performance of the simulation model. RQ 2 is formalized to analyze performance of the system by implementation of this concept.

RQ 2: What are the impacts in terms of performance of Industry 4.0 on a specific case of mass customization model?
This RQ will help us in getting some tangible results and statistics from our simulation model. Based upon which we can purpose certain strong suggestions for future mass customization industries. This leads us to the formulation of the third research question.

RQ 3: What suggestions can be proposed to the future mass customization industry for the implementation of Industry 4.0 concept?
By answering this question, we will purpose some suggestions and future implementation for the development of this concept in current mass customization industries. It will be based upon the results that we obtain from the answer of RQ 2.

3 Conceptual Design

In this section, the detailed study is performed to evaluate the characteristics of Industry 4.0. The aim is to develop the conceptual designs of mass customization system with the concept of Industry 4.0 and without Industry 4.0 characteristics so that they be compared in simulation part.

3.1 Conceptual Model Characteristics

The concept of Industry 4.0 is composed of three main pillars, i.e., smart product, smart machines, and augmented operator [8]. The main idea behind the smart product is to extend the role of the workpiece to an active part of the system. The products receive a memory on which operational data and requirements are stored directly as an individual building plan. In this way, the product itself requests the required resources and orchestrates the production processes for its completion [9]. This is a requirement to allow self-configuring processes in highly modular production systems.

The second pillar, smart machine, defines the process of machines becoming more autonomous and intelligent without any human interference even at the level of troubleshooting. The traditional production systems will be replaced by a decentralized self-organization enabled by cyber-physical system (CPS) [10].

They portray autonomic components with local control intelligence, which can communicate to other field devices, production modules, and products through open networks and semantic descriptions. In this way, machines can self-organize within the production network. Production lines will become so flexible and modular that even the smallest lot size can be produced under conditions of highly flexible mass production. Additionally, a CPS-based modular production line allows an easy plug-and-play integration or replacement of new manufacturing units, e.g., in case of reconfiguration [8].

The last pillar, augmented operator, provides the unique approach for technological support of the worker with the highly modular production environment. In fact, it is important to understand that Industry 4.0 is not leading toward workerless production systems. Human operators are considered as the most flexible parts of the system that can be more adaptive in those challenging environment. They can perform great variety of jobs including specification check, monitoring, and verification of production strategies. Also, they can manually intervene in the autonomous production process whenever it is required. This technological support will surely make workers capable to realize their full potential and adapt the role of a strategic decisionmaker and flexible problem-solver. Indeed, that will make possible to handle the raising technical complexity of the system [8].

Customer involvement is also becoming the most crucial part of mass customization industry because of high dependence on customer's product needs. It is extremely important to not just include customer in product variety but also in the complete supply chain until delivery of the product. Hence, the integration of Industry 4.0 concept with MC requires four pillars to be implemented:

1. Communication between machines (smart machines)
2. Communication between product and machine (smart products)
3. Communication between humans and machines (augmented operator)
4. Customer involvement

3.2 Discrete Event Simulation Model

To study the impacts of Industry 4.0 upon mass customization, we developed a model that implements the four abovementioned pillars. It will be difficult to simply accept the results from one model without any comparison so we decided to build two models. One model will contain all the characteristics of Industry 4.0 while the other will not. However, all the properties, dimensions, and processing time of physical objects and equipment should be the same to simulate the same situation. Also, it is important that conceptual model should be generalized so it can be adapted to different industry types. Our motivation is to compare these two models to draw some concrete results. Below mentioned are the base models upon which we will build simulations. To simplify the case, we have just chosen picking and assembly units for simulations.

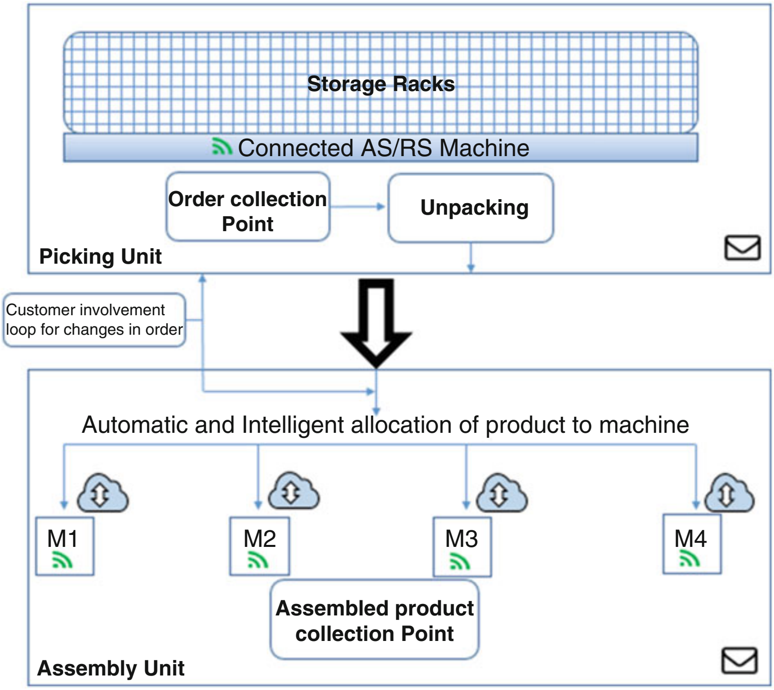

Fig. 1 Conceptual model with Industry 4.0

Figure 1 describes the customization model with Industry 4.0 concepts. In this model, orders are automatically fed into the automated storage and retrieval system (ASRS) machine as soon as they are received from the customer. The ASRS machine will automatically collect the respective items from the storage racks and puts them into the order collection point. To update the customer, an automated email will be sent to the customer describing that "your order has been collected and you have certain time left in case you want to change your order." Then order components will be unpacked and proceed to the assembly unit. Initially, in assembly section the order will be sorted. Those orders that need modification (as per customer request) will be routed back to the picking unit while other orders will be allocated to the assembly section by considering the following parameters in the account:

- Number of orders in each assembly line
- Workload on each assembly processor

In the future, this model can also consider time of delivery, order deadline, and urgent orders for premium customer. But in this model, these parameters are not considered. In the end, the orders will be collected and assembled at the product collection point and delivered to the customer along with an automatic email notification of dispatch order. Table 1 defines how we can implement the pillars of Industry 4.0 on MC model in real environment as well as in simulation.

Table 1 Implementation of Industry 4.0 pillars

Pillar	Implementation in the MC model with Industry 4.0
Communication between machines	Machines can upload their current state on cloud where its data is examined and instructions are sent to each machine
Communication between product and machine	Connectivity allows communication of product with machines by sharing their current state on cloud and giving them instructions to proceed in an optimized way
Communication between humans and machines	Humans can visualize the performance of each machine through cloud data analytics and give instructions to machine at any time
Customer involvement	Customers are updated at each stage of its order processing as product status is updated on cloud at every instant

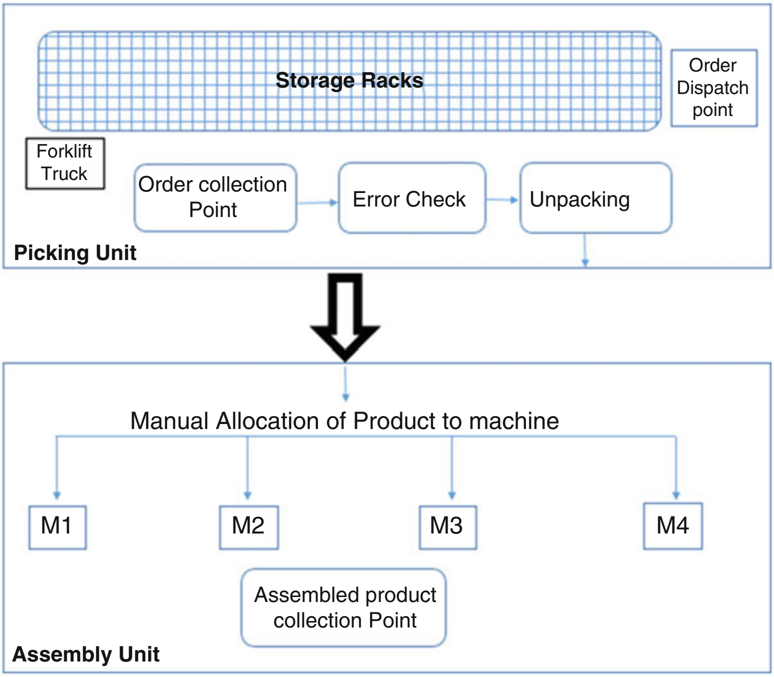

Fig. 2 Conceptual model without Industry 4.0

Figure 2 describes the current scenario of mass customization industry (i.e., without Industry 4.0 concepts). In which, forklifter collects a manual order from order dispatch point and collects the respective items from storage racks. Since all these processes are manual, there is a great probability of error. That's why an error check process will be performed on all the orders, and then items will be unpacked and will proceed to the assembly unit. In the assembly unit, the orders will be allocated randomly to each assembly machine without considering any parameter. At the end, the orders will be collected and assembled at the product collection point and delivered to the customer.

4 Simulation Model Development

Two simulation models based on the conceptual models have been developed on the FlexSim software. The purpose behind building two simulation models is to compare the results obtained at the end. In these simulation models, we have tried to replicate the actual scenario of our current customized industry model and tried to put as much reality as possible. These simulation models contain storage racks, pallet source, transporter, combiner (order collection point), error check points, separator (only for orders with errors), unpacking processor, conveyers, assembly processor (i.e., 1/2/3), and delivery queues. As described earlier, all the properties, dimensions, and processing time of physical objects and equipment are kept the same in both models, so that our results become irrelevant of physical characteristics of objects and describe only differences observed by implementing the Industry 4.0 concept. We simulated both models for the run time of 28,800 s (8 h) and replicated these simulations 250 times to take average results. As all the machines are subject to certain degree of tolerances (normal distribution within +/− 5%) in its operation, little variation is observed in result of each single simulation. To deal with this problem, we decided to take the average results till a certain number of replication, after which no significant variation in average results is observed. After 250 replications, results were not changing significantly that is why we fixed the number of replication to this limit. Figures 3 and 4 show simulation models developed in FlexSim software.

The table below highlights the main difference between Industry 4.0 and without Industry 4.0 model and gives in-depth view to understand both models along with their characteristics.

5 Simulation Output Analysis

Simulation models are developed to generate output for analysis. Since our model is the representation of a real system, it will be used to understand the behavior of a real MC system.

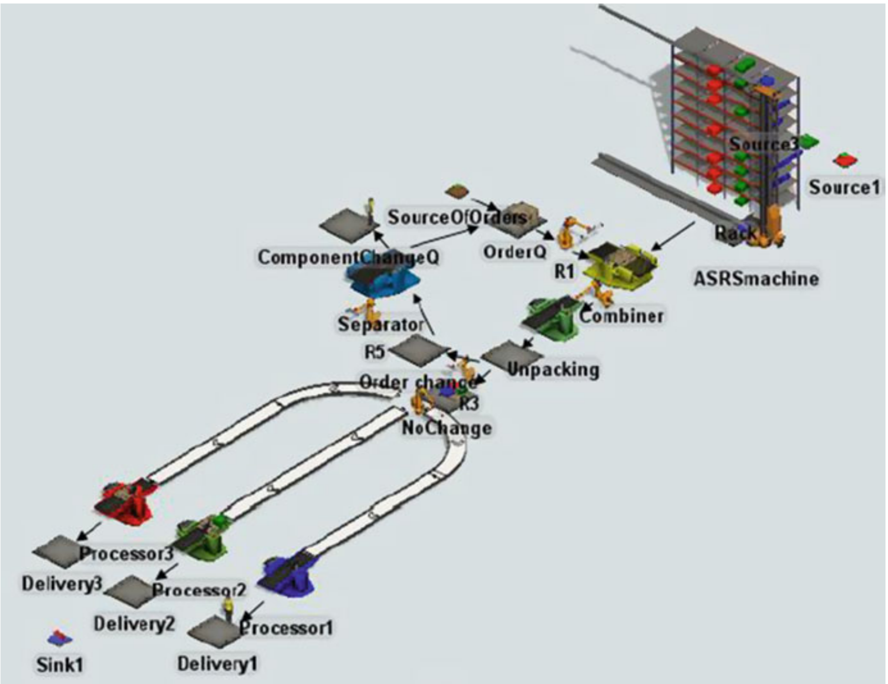

Fig. 3 Simulation model with Industry 4.0

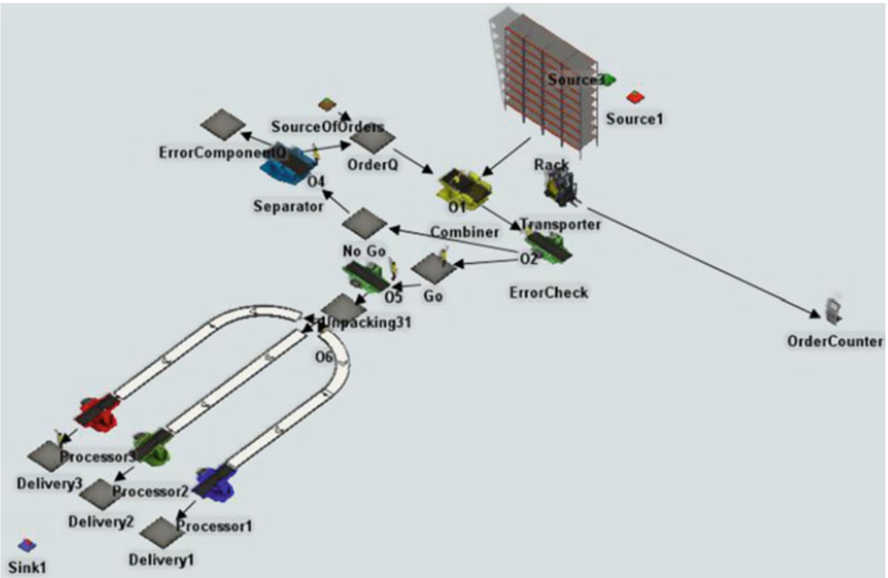

Fig. 4 Simulation model without Industry 4.0

Table 2 Differences between two models

Point of differences	Model with Industry 4.0	Model without Industry 4.0
Allocation strategy to assembly units	Account number of orders in each assembly line Account workload on each assembly processor.	Random allocation by operator
Order picking system	Centrally connected ASRS	Manual forklift truck
Machine communication	Yes	No
Product and machine communication	Yes	No
Error check operation	No	Yes

5.1 Simulation Methodology

Careful statistical analysis is paramount when using output from a discrete event simulation model. Inputs to a model are decision variables (i.e., that are controlled by the decisionmaker). In these models, decision variables are mainly differences in allocation strategies that resulted from machine-to-machine and product-to-machine communication (described in Table 2). On the other hand, output from model provides information on the consequences of setting the decision variables in a certain manner. For measuring the performance of the system (i.e., output), we selected the following important KPIs:

- Order completion time
- Waiting time in queues
- Utilization rate of machines
- Customer satisfaction

The outputs gathered from the multiple run (250 replications) are combined to provide a basis for conclusions and inference. Also, confidence interval of 90% is used to estimate the means of output or response variables which provide the foundation for inference and decisionmaking.

5.2 Key Performance Indicators (KPIs)

Key performance indicators are the set of quantifiable measures that can be used to measure the performance of a certain process over time. To measure the performance of our simulation, we formulated some KPIs based upon which we can decide the real impact of Industry 4.0 on the specific case of mass customization system. As we have developed two models (i.e., one with Industry 4.0 concept and the other without it), our motivation is to compare the above KPIs from both models and come up with a concrete conclusion to make a real progress in this topic of research.

5.2.1 Order Completion Time (OCT)

The order completion time is time that is required to complete a single order. It considers the time that it takes at each process during its processing. We performed 250 replications of simulations and collected mean of order completion time along with its standard deviation. The more replications we make, the closer results to real model can be obtained. It is one of the important KPI that can impact the implementation of Industry 4.0 concept on future customized industries. Figures 5 and 6 describe the result summary of MC model with and without Industry 4.0 concept with mean and standard deviation in Table 3.

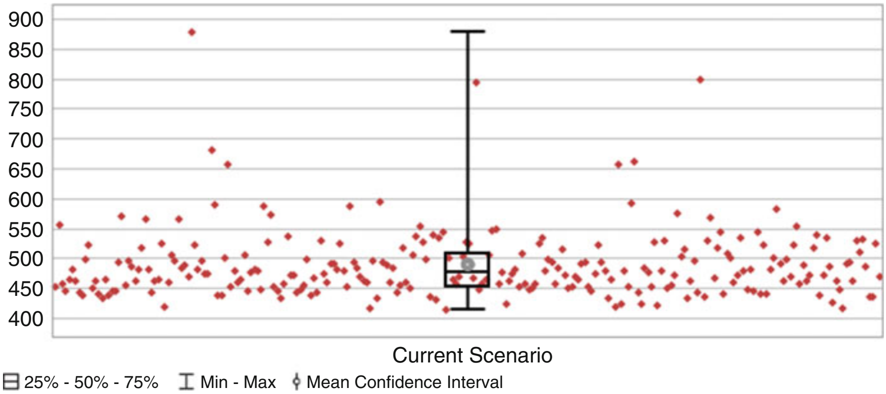

Fig. 5 OCT with Industry 4.0

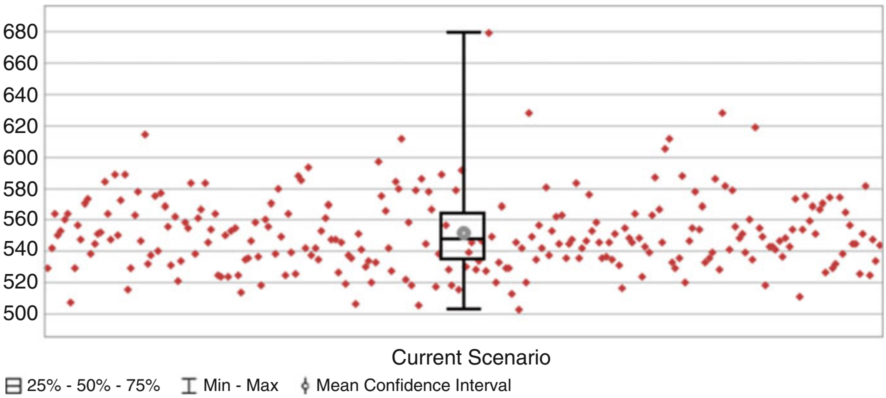

Fig. 6 OCT without Industry 4.0

Table 3 Order completion time results

250 replications	Mean (90% confidence)	Sample std dev
With Industry 4.0	484.5 < 490.8 < 497.2	60.6
Without Industry 4.0	550.5 < 553.6 < 556.6	28.9

It can be observed by comparing the above results that the smaller mean is obtained in the case of mass customization model with Industry 4.0 concept. It clearly means that on average, it will take less time to complete a single order with the implementation of Industry 4.0 concept. Model with Industry 4.0 concept will have **11.23%** less order completion time than mass customization industry without Industry 4.0 concept (i.e., current customization industry).

5.2.2 Waiting Time in Queues (WTQ)

The second extremely important KPI is the waiting time in queue. Since we used conveyer for order flow from one unit to another, most of the waiting time will be observed at conveyers, and we calculated only that time. The higher the waiting time of the order, the more cost it will add to the manufacturer. Also, the variance of waiting time is of keen importance because if it is higher than the waiting time, it would be more unpredictable and vice versa. Figures 7 and 8 describe the result summary of WTQ from mass customization model with and without Industry 4.0 concept with mean and standard deviation in Table 4.

Great difference can be observed by comparing the results of waiting time for both models. The average waiting time for the mass customization model with Industry 4.0 concept is far more less than the model without Industry 4.0 concept. For all the replications of the first model, the mean waiting time of 11.64 s has been observed with no standard deviation. While on the other hand, for the second model, the mean and standard deviation of waiting time are varying a lot. If we compare the results for 250 replications, then nearly **77.8%** of waiting time can be reduced, and nearly 0 standard deviation can be achieved. It means we can purpose fixed lead time of order to our customer with extremely little variance.

5.2.3 Utilization Rate of Machines (UR)

Utilization rate of machines is a quite important KPI to measure. As the processing time and physical parameters are the same for all processors in both models, they will not have any major change in time. But it will be significant if we can measure the change in idle time of transporter and ASRS machine. So, we calculated the average utilization rate (AUR) for both and recorded 250 replications. To calculate the average idle time, we subtracted average utilization rate from one. Figures 9 and

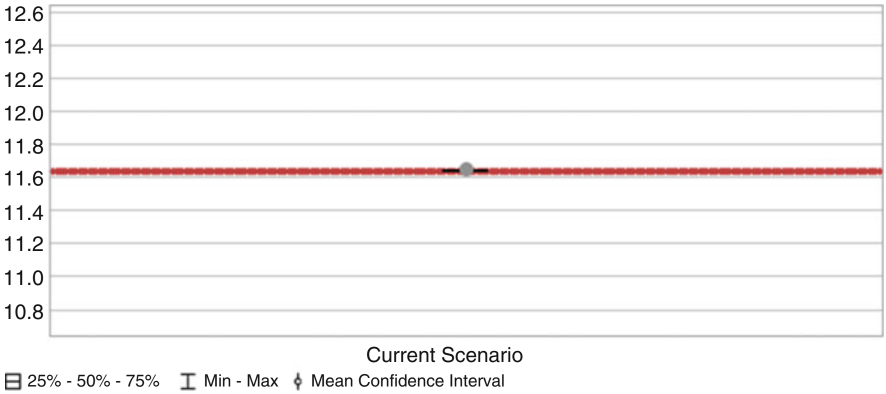

Fig. 7 WTQ with Industry 4.0

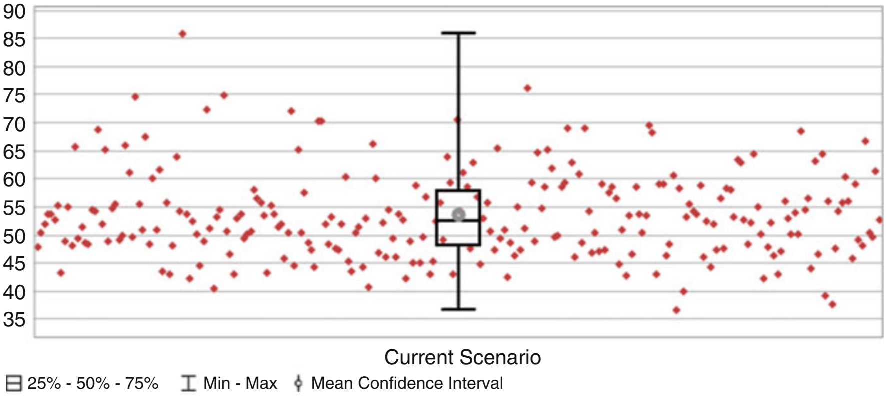

Fig. 8 WTQ without Industry 4.0

Table 4 Waiting time in queue results

250 replications	Mean (90% confidence)	Sample std dev
With Industry 4.0	NA < 11.64 < N/A	0.00
Without Industry 4.0	51.77 < 52.50 < 53.22	6.88

10 describe the result summary of UR from mass customization model with and without Industry 4.0 concept with mean and standard deviation in Table 5.

It can be clearly observed that there is a great difference between the average utilization rates of both models. If we compare the results of 250 replications of both models, nearly **22%** of an increase in utilization rate is observed. It means there will be a great gap of increase in efficiency of the system if Industry 4.0 concept is implemented.

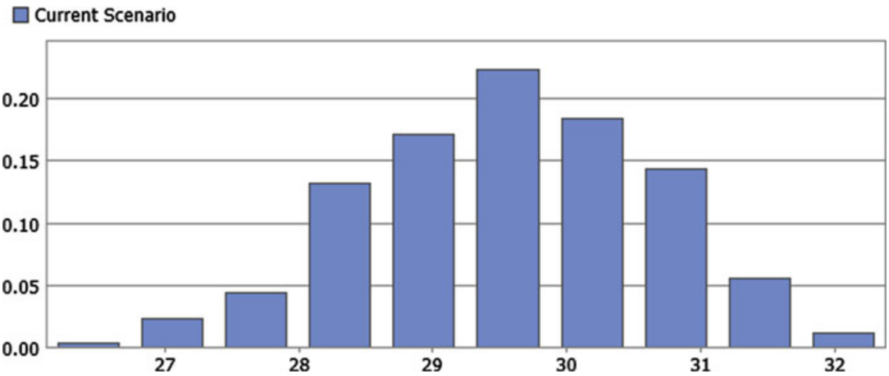

Fig. 9 UR with Industry 4.0

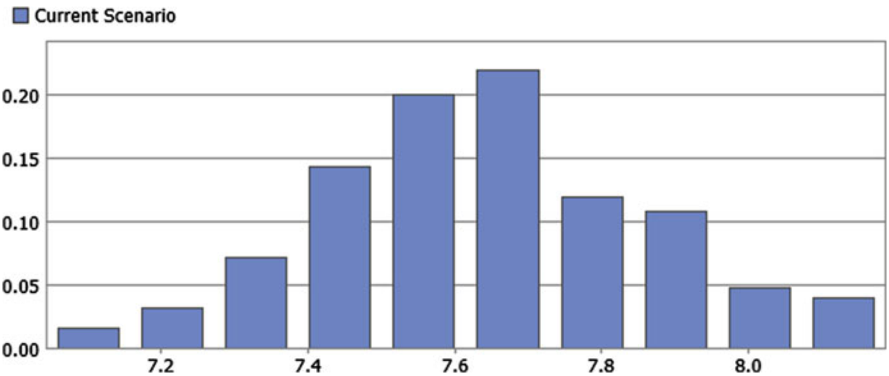

Fig. 10 UR without Industry 4.0

Table 5 Utilization rate results

250 replications	Mean (90% confidence)	Sample std dev
With Industry 4.0	29.44 < 29.56 < 29.68	1.10
Without Industry 4.0	7.623 < 7.646 < 7.699	0.221

5.2.4 Customer Satisfaction (CS)

Customer satisfaction is a keenly important KPI for future mass customization industry but extremely difficult to measure directly from the simulation model. We decided to follow an assumption that customer satisfaction is directly proportional to the number of order completed on time (OCOT) so if we measure that number then we can suggest the same about the customer satisfaction as well. We set the order completion window limit between 0 and 700 s and calculated the number of

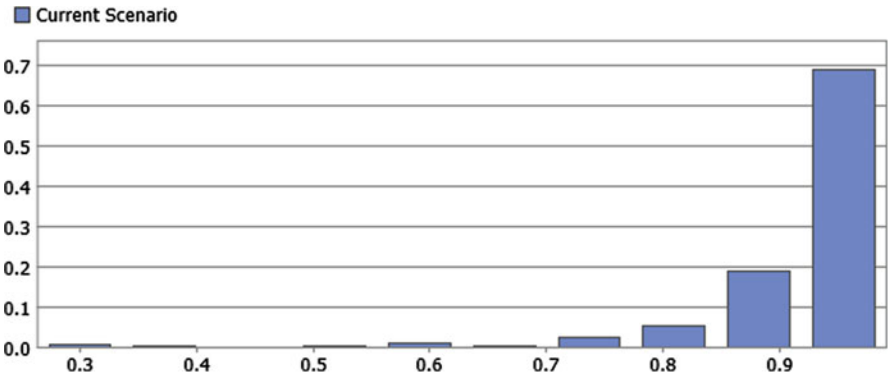

Fig. 11 CS with Industry 4.0

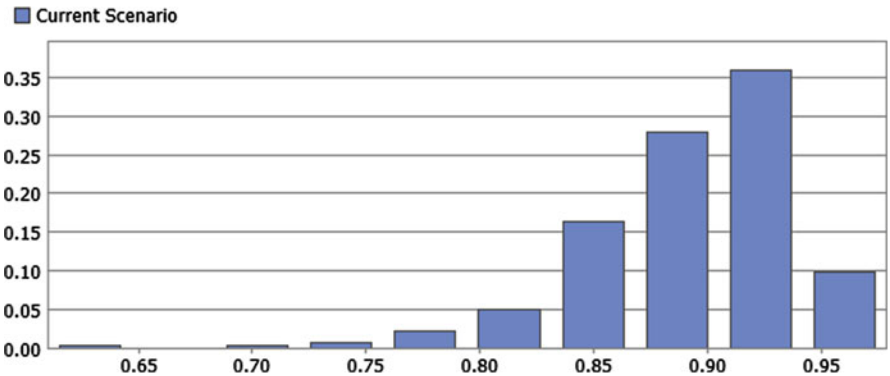

Fig. 12 CS without Industry 4.0

Table 6 Customer satisfaction results

250 replications	Mean (90% confidence)	Sample std dev
With Industry 4.0	0.906 < 0.916 < 0.927	0.100
Without Industry 4.0	0.8740 < 0.8810 < 0.8881	0.063

orders that completed in that window for both models. Figures 11 and 12 show the result summary of CS upon average order completed on time from MC model with and without Industry 4.0 concept with mean and standard deviation in Table 6.

It can be clearly observed that there is a significant difference in “average order completion on time” for both models. Nearly **3%** increase in order completion rate can be seen by the implementation of Industry 4.0 concept. This percentage increases matters a lot for companies whose product is dependent upon customer preferences. Moreover, with Industry 4.0 concept, more orders are completed on time while there is a lot of scattered results for the model without Industry 4.0 concept. It means great precision and accuracy can be achieved with the implementation of Industry 4.0 concept that will lead to a great customer satisfaction.

5.3 Result Summary

In this section, we have summarized all the results that we obtained from our simulations and their impacts on our selected KPIs. The positive impacts of Industry 4.0 implementation can be clearly seen on each KPI, but their percentage is varying differently.

A decrease of 11.23% in average order completion time is observed in the model with Industry 4.0 concept. If order completion time for each order is lesser, it is possible to fulfill more orders on the same day. It means that Industry 4.0 will not only lead to a higher process efficiency but also higher financial benefits for the company.

In the same way with the implementation of Industry 4.0 concept, the waiting time of the order in queue has drastically decreased. Approximately, 79.8% of decrease is observed in this case. The main reason behind this large change is due to the difference in order allocation strategy to the assembly unit. The communication between the machines will allow them to measure the load and processing time of order on each production unit and take intelligent decision by measuring the least possible time for upcoming order in the queue. This type of intelligent decision is very difficult to take for manual operator in current customized industry. Hence, the communication between the machines in Industry 4.0 concept will benefit a lot of future MC.

Idle time for the machines was another interesting KPI that has been impacted significantly by the implementation of Industry 4.0 concept. It should be kept in mind that processing time and physical parameters of all the processors are the same for both models. So, it is not possible to have difference in processing time of processors while the only difference is observed if we compare transporter (in without Industry 4.0 model) and ASRS machine (in Industry 4.0 model). As transporter always go to order collection point for collection of picking list while in case of ASRS machine it receive an automatic update of order in its system so a there is a room to increase the productivity of the system. Decrease of 22% has been observed in the idle time from transporter to ASRS machine by implementing the concept of Industry 4.0. That will lead to a great cost saving and increase in process efficiency.

Lastly, customer satisfaction is among the most important KPI that is impacted by the implementation of Industry 4.0 concept. Unfortunately, it is extremely difficult to measure its impact directly by simulation so we need to measure the factor that can lead us to customer satisfaction. One of the most important factors that can impact the customer satisfaction is “percentage of orders completed in time.” The higher the orders completed on time, the higher will be the customer satisfaction. An increase in nearly 3% of “average percentage of order completed on time” is observed by the implementation of Industry 4.0 concept.

6 Conclusion

This research work presents the deep study of impacts by the implementation of Industry 4.0 concept on a specific case of mass customization industries. As Industry 4.0 is an extremely vast concept, it is difficult to generalize its implementation on all kinds of industries. Hence, we only focused our research stream to mass customization industries.

The impact of Industry 4.0 seems to be promising especially for mass customization systems in relevance to product completion rate on time, customer satisfaction rate, customer involvement, utilization rate of machines, and waiting time in queues. The results obtained after simulation depict a clear picture in favor of Industry 4.0 concept. The implementation of this concept can lead to numerous benefits for the future MC industries. It will not only increase the financial benefits for the firm but also help in obtaining greater process efficiency and customer satisfaction. Unfortunately, literature about this topic is very limited. Therefore, it is of keen importance to address this subject. Although the implementation of this concept is facing some technical challenges, the current innovations in information technology (i.e., cyber-physical systems, cloud computing, Internet of things, RFID, etc.) hold a full potential to implement this concept in a real environment. No doubt, the key hurdle is the huge investment that is required to put this concept into reality. So, investors need to clearly understand the risk and opportunity of their investment. Indeed, our study will help them in understanding the opportunities and criticalities concerned with the implementation of this concept.

There are certain issues that can be dealt in future research to show a more deep understanding of benefits that can be obtained by implementation of Industry 4.0 concept. One of them is the allocation strategy of Industry 4.0 simulation model. For the meantime, we have just considered the load on each assembly unit or number of order in each conveyer, but for the future work, we can also consider the request for urgent orders and time left for each delivery. Those parameters can provide more deep results for MC industries. Another important parameter is the level of customization for the customer. In our model, we have considered only the assembly level of customization for customers. In the future, this level of customization can be increased to design or fabrication level as well. This will increase the level of customer engagement in the process, and greater customer satisfaction can be achieved through it.

Moreover, different KPIs can be set for future work to make results more diverse and increase the scope of work. It can lead to understand the benefits of the industry 4.0 implementation, to be more visible and better to understand.

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Part III
Mass Customization and Sustainability

Mass Customization and Personalization: A Way to Improve Sustainability Beyond a Common Paradox

C. R. Boër, C. Redaelli, D. Boër, and M. T. Gatti

Abstract While the entire world is measuring the energy spent in saving the environment, and sustainability is one of the trendiest words, the real meaning of the term and the way of making it more concrete is still not clear.

Which is the perception of "sustainability" among academics, industrials, and common people? This perception appears as basis of a generally accepted paradox that brings the market players discussing about "recycling and renovating" and not measuring real users' needs.

The present paper tries to also understand how historically the market has produced the above paradox based on the economic value that dominates the global community.

The analysis of the confusion about "end-of-life" and "beginning-of-life" of a product among consumers demonstrates the generation of a collective contradiction. The paradox of our society is in fact based on the consciousness of the "end-of-life" of the mass-produced products but with total ignorance of the waste energy for products never sold ("beginning-of-life").

The paper proposes a change in production paradigm as a possible solution to go beyond the paradox. Where today mass production (MP) is still the dominant paradigm, mass customization (MC) and personalization is becoming more accepted and feasible also, thanks to the technological developments and innovations.

Keywords Sustainability · End-of-life · Beginning-of-life · Mass customization

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1 Introduction

"Sustainable" (and sustainability) was forged by the World Commission on Environment and Development (WCED) better known as the Brundtland (prime minister of Norway) Commission [1]. It was created by the UN in the 1980s to face the heavy deterioration of the environment and natural resources. The commission released a document titled *Our Common Future* in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. But the paragraphs below retrace the history of concepts like development, progress, and sustainability.

The demand of raw materials, their transport in different places, and consequently the impact on the environment were historically a concept already known by the ancient populations; there are proves in Plato, Pliny the Elder [3], Columella [4], and many other historians in different civilizations. They were already worried for the environment degradation and recommended to pay attention for maintaining the "everlasting youth" of the earth [4]. Jumping in the history of civilization in the eighteenth century, the population grows a lot, and in the following century it concentrated in urbanized areas. That created a high demand of coal as principal source of energy for cities and industries. During the age of industrial revolution and more than a century before, the term "sustainable development" came into general use, and several publications appeared which dealt with what we would today call sustainable development [5].

In the first half of the twentieth century, oil became the primary source of energy, and scientists raised the alarm that oil supplies might be exhausted soon starting the discussions about the limitations to the supply of raw materials and energy sources and warned against wasteful consumption [6].

The twentieth century was a period of alternation between optimistic and pessimistic outlooks with regard to human development. But soon after World War II, an unprecedented economic boom paved the way of rising living standards worldwide. It was, however, during this period of industrial and commercial expansion that the environmental crisis started looming larger on the horizon, forcing people to change their basic assumptions about growth and development [5].

And in the 1960s, because of a period of population growth, but most of all because of the industrial and scientific development linked with commercial demand, the people started reading about pollution, resources depletion, and population growing. In those years, green organizations were established.

The term *sustainability*, a noun used in ecology to refer to a condition that can be maintained over an indefinite period of time, was introduced on a more regular basis than before into development discourses [5]. At the start of the 1970s, the term "sustainable development" was coined, probably by Barbara Ward founder of the International Institute for Environment and Development [7].

And finally the story is back to the United Nation Brundtland Commission. The report expressed the belief that social equity, economic growth, and environmental maintenance are simultaneously possible, thus highlighting the three fundamental components of sustainable development, which later became known as the triple bottom line [3, 6]:

- The environment
- The economy
- The society

Many critics were moved to this international text; one for all is in EURACTIVE 2002: the document did not question the ideology of economic growth, and it did not adequately challenge the consumer culture; it was serving comfortably the neoliberal interest [8].

Governments, businesses, and civil society together with the United Nations have started to mobilize efforts to achieve the Sustainable Development Agenda by 2030 [9]. In 2015, countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals. By scrolling the 17 goals of the agenda, it's clear that well-being and equality for everyone in the world is the major goal and industrialization does not have to be blind and indiscriminate increasing divisions. The 12th goal of the agenda states: "By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse" [9].

But what is the common perception of the term "sustainability" today? Are we enough oriented to the ecological/environmental problems today? And how much do we abuse environmental issues?

Walking around a nice lake in the center of Guyan in China, where every year the World Eco Forum Global (www.en.efggy.com) takes place, it is possible to read tens of nice posters pasted in the walk promenade with the purpose to inform about the different environmental issues. One of them says: "In our way of life, we should elevate the low carbon and green consumption concepts instead of being in excessive pursuit of material wealth and enjoyment." Nobody is against such statement, but what can we learn from this declaration? Is this something that young people can learn and increase their awareness about environment? Furthermore, why and how we arrived to have a society where it is normal to "excessively pursuit material to assure wealth and enjoyment."

The purpose of this paper is not to give all the answers but to try to push forward some innovative visions that have been already worked in the last few years by different research projects in the field of sustainability in production and product innovation. The goal of the paper demonstrates that it's possible to "rationalize inefficient [. . .] encourage wasteful consumption by removing market distortions" in line with another objective of the agenda for sustainable development into 2030 [9].

2 The Paradox of the Modern Society: Be Sustainable in the Wasteland

Nowadays, sustainability has become such an abused term that people do not consider anymore what it really means, that is, the basis to explain the social paradox experienced by the humanity.

The paper focuses on one aspect of the wide world market, giving a concrete example about the shoes industry, use, and waste. This choice has two main purposes:

1. To discuss the perspective about environmental issues that have been lost and the common user's attitude: he is not able to question the communication about ecology and sustainability anymore.
2. To show a concrete example to move from a theoretical concept to something tangible, part of the common experience, something that everybody can grasp and share, criticize, and contribute to.

The paradox is something so simple but a revolution in the way of considering the sustainability: the general preoccupation is to face the end-of-life of the products, but we forget to consider the production process from the beginning when it's decided to produce "things" that nobody will ever buy. Are these "unused" objects trash or waste?

2.1 Trash and Waste

First of all, it is essential to define the difference between "waste" and "trash," since many people confuse the two terms. Here, below are definitions from the dictionary [10]:

- Trash:
  - Anything worthless, useless, or discarded; rubbish
  - Useless or unwanted matter or objects
- Waste:
  - An act or instance of using or expending something carelessly, extravagantly, or to no purpose
  - An object the holder discards, intends to discard, or is required to discard [11]

Based on the definitions reported, "trash" term seems to the authors much more correct instead of "waste" when the produced goods are worthless, useless, and not even purchased.

Historically, the first landfill was in Crete 3000 BC where Knossos digs large holes for refuses. In 2000 BC, China developed methods of composting/recycling waste and in particular bronze for reuse [12]. But surely the garbage was in quantity

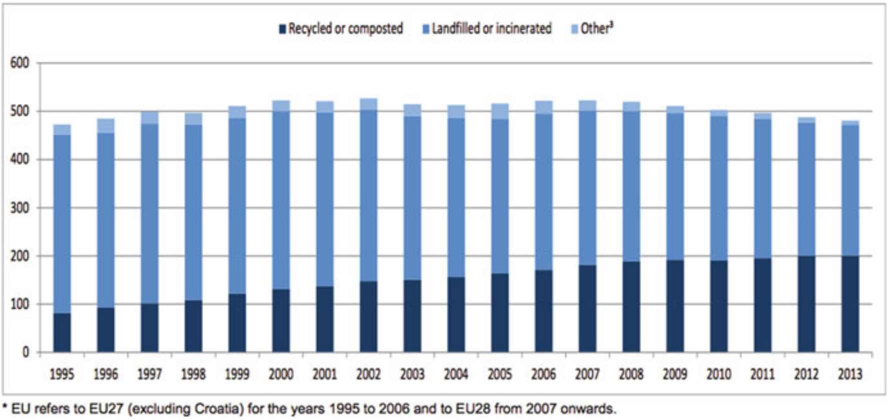

Fig. 1 Kg of waste generation and treatment: EU 1995–2013

Table 1 Electricity usage in the word for 2008

Source of electricity (world total year 2008)							
–	Coal	Oil	Natural gas	Nuclear	Renewables	Other	Total
Average electric power (TWh/year)	8263	1111	4301	2731	3288	568	20,261
Average electric power (GW)	942.6	126.7	490.7	311.6	375.1	64.8	2311.4
Proportion	41%	5%	21%	13%	16%	3%	100%

Data source IEA/OECD; www.iea.org

and quality deeply different from the present one. Today in Europe each person generates 481 kg of waste per year (data referred to 2013) [13]. The amount of municipal waste generated varies significantly across the EU Member States. With less than 300 kg per person, Romania, Estonia, and Poland had the lowest amount of waste generated in 2013, followed by Slovakia, the Czech Republic, and Latvia (all just over 300 kg per person). At the opposite end of the scale, Denmark (747 kg per person) had the highest amount of waste generated in 2013, well ahead of Luxembourg, Cyprus, and Germany with lower amounts but above 600 kg per person, and Ireland, Austria, Malta, France, the Netherlands, and Greece with values between 500 and 600 kg per person (Fig. 1).

The laws for recycling brought forth to a relatively new industry for waste treatment. From the Greek law (500 BC) that ratified to have the garbage dumped at least 1 mile from the city [12], to the different waste treatments considered today [13]:

- Landfill means the depositing of waste into or onto land, including specially engineered landfill and temporary storage of over 1 year.
- Incineration means thermal treatment of waste in an incineration plant.

- Recycling means any recovery operation by which waste material is reprocessed into products, materials, or substances whether for the original or other purposes, except use as fuel.
- Composting means the biological treatment (anaerobic or aerobic) of biodegradable matter resulting in a recoverable product.

Given the definition above of "trash" and "waste," then it is clear that, if the family acts consciously, then all those items are trash and not waste.

3 A Concrete Example of the Paradox: The Shoe Production, Use, Trash, and Waste

To better clarify this concept, let's take one product that everybody or every consumer has used, is using, and will be using: a pair of shoe. On this product, we will build the concrete example we have mentioned.

To understand the dimension of this example, let us answer the following questions:

- *How many pair of shoes are in average in a closet?*
- *How many pair of shoes each consumer buy every year?*

It is a way to bring the average consumers to enter and immerge themselves in a real environmental problem that they normally never think about. We buy a lot of shoes, enough to fill more than few closets. Each of us has different pairs for different occasion of use and different seasons or weather conditions. It's estimated [http://cec-footwearindustry.eu/] that *20 billion pairs of shoes are produced* annually, and unfortunately, roughly *300 million pairs are thrown away* each year, too.

Like for clothing, shoe trash occurs entirely too much and it is 100% avoidable. The shoe manufacturing process is a chemical-intensive process. Ethylene vinyl acetate, a material commonly found in the midsole of running shoes, can last for as long as 1000 years in a landfill. When considering the sheer volume of shoe thrashing, it's environmentally irresponsible to toss shoes in a landfill where they'll impact the planet for centuries. Research has been ongoing to solve this issue [14].

But the case study is focused on the waste of shoes as a final product and not on the trash of the production process itself and more in general. In other words, following the definition, it's about the act of using or expending something carelessly, extravagantly, or to no purpose, in the case of the example, the production of tons of shoes that are not used.

The industrial production is mainly based on the production paradigm of mass production (invented by Ford with the famous Model T), it is efficient to bring consumer's goods to the clients, but it is highly inefficient from an energetic point of view. And we will see later the reason. The point is that the consumers ignore how many of these products have been sold at the end of the season or at the end of the year, and probably many stakeholders too. The answer is that for 100 pair of shoes produced, 80 are sold but 20 are not [15]. *And here is the paradox of our society: we all focus on the end-of-life of our products, but we miss the beginning-of-life when we produce "things" that nobody will ever buy.*

It's important to understand what does it means to produce 20% of shoes that are never sold. It means that the factory has consumed 20% of energy and materials for products that nobody wants and will never want. It is important to understand the values or numbers of this phenomenon, for sustainability comprehension. It is important to show the dimension of a problem and not only to mention that there is a problem.

3.1 The Energy Waste for Unused Shoes

The total energy consumed in the world can be subdivided in three equivalent parts: transportation, buildings, and production.

One third is consumed by the industrial production (from transformation of raw materials up to the final product). There are thousands of power stations based on fossil fuels, water, nuclear, solar, wind, etc. We will not enter here in the debate about which source of energy is more sustainable. But we may assume for our discussion that we take an average power station of 500 MW [16_ NYT].

Then according to available data, the number of stations will be 4622. One third are dedicated to production that is 1541 power stations. Calculating the average energy necessary to produce 20 billions pair of shoes (we know what is the energy to produce one pair of shoe [15]) and then calculate how many power plants are necessary. The total number of power plants to produce the 20 billions pair of shoes is therefore 25. Compared to the total number of power plants in the world, it is only 0.54% but it is 1.62% of the power plants dedicated to production! That will be ok because anyway we need those shoes. Unfortunately, 20% of those shoes are unsold. Let us calculate the average energy necessary to produce 4 billions pair of shoes or the 20% of unsold shoes and then calculate how many power plants are necessary. Again a simple calculation brings us to five power plants of 500 MW each one.

It also means that around the world there are five power plants working 24 hours for 365 days to produce those unsold shoes and consuming fossil fuel or nuclear material or water for nothing!

4 The Paradox Solution: Changing the Production Paradigm

How the paradox can be solved? Could we reduce numbers or even eliminate this problem?

The problem has been generated by the mass production paradigm. It focuses on average consumers' needs but it does not focus on the real market size. And therefore in order to sell the 80% of its production, it has to produce 100% of shoes with the 20% of unsold.

The mass production paradigm tends to produce more products than are really needed because it is "market oriented in an approximate way"

- Mass production knows *the trends of the market* (approximately).
- Mass production knows *the volume of the market* (approximately).
- Mass production knows *the time to the market* (approximately).

The problem is the "approximately": it is creating the "waste" that we have presented. If we could predict in an accurate way the "approximately," then also the waste will be reduced and even eliminated. Moreover, the marketing habits of pushing products toward customers use big advertisements and attention-grabbing claims to put products into the minds of customer supporting the mass production system inserting needs where there are none.

However, nobody has ever taken into consideration the beginning-of-life. All (producers as well as consumers) focus on the end-of-life of the products thinking about recycle, reuse, lower impact on the environment, etc. The trend was even designing products based on reusable components, recycled, or biodegradable following the cradle-to-cradle concept, take the materials from the cradle of nature but return it to the cradle of nature [17].

4.1 The Mass Customization and Sustainability

Mass customization contributes to sustainable business development by tackling future waste before its production. By producing goods tailored to the customers' need and wish, mass customization ensures to produce only what is needed [15] (Fig. 2).

If we look at the evolution of production [19], we can see that from the (1) craft production (when the products were essentially made only on the request and requirement of the single customer), we went to (2) mass production (when the products were designed and produced mainly for the average consumer but pushed on the market before the consumer could even see the product – Ford Model T). We are now very slowly entering the era of (3) mass customization when the products are not only designed for each single customer but also produced only when the customer has already bought the product. We can see that there is not only an "evolution" of the production paradigm but also an "involution": from the focus on the customer, to the focus on the market, and then back to the focus on the customer.

The trend is bringing the production to a still innovative way to produce "things" realizing only:

- What is necessary
- When it is necessary
- To customer's specifications

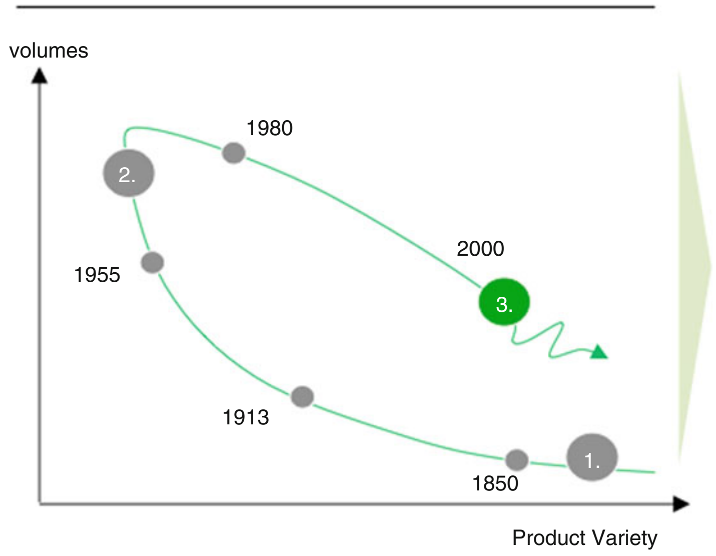

Fig. 2 Industrial evolution and involution trend

5 Beyond the Paradox with Mass Customization Shoe Production

Footwear industry is a powerful example of a very large potential of the use of this new production paradigm. Photo number 2 shows a shoe produced according to mass customization principles, which clearly indicated that these shoes are made for only one customer with his name and identification number for the system (Fig. 3).

Of course the production cycle and processes must be adapted. Simplifying from the consumer (in this case one of the authors) point of view:

- *Mass Production* – the consumer goes to the shop where there are hundreds of available pair of shoes. He/she chooses and tries several models until he/she is (more or less) satisfied; for me I am never 100% satisfied because my left foot is slightly shorter than the right foot. I always ask to try the number 41 for the left foot and the number 42 for the right foot, but the shop never wants to sell me a pair of shoes that are of different sizes! The client, me, is therefore not satisfied. At the end, the consumer pays and walks out of the shop with the pair of shoes.
- *Mass Customization* – the consumer enters the shop where there are only few real pairs for each model of shoe, and the client can touch and feel the material. Then the user's feet are scanned with a 3D machine, very similar to a 2D photocopy but in 3D for the two feet. The computer analyzes the geometry of the feet and based on the client's desires and his/her daily needs (whether in the place of living, work in or outdoor, occasion of use), and finally it proposes the best model of shoes. The client can still choose color, materials for the upper and for the sole and even the insole, strings, etc. Finally the computer, in communication with the

Fig. 3 Customized shoe

factory, proposes a date when the customized shoes will be available. If the client agrees, he/she will then pay and walk out of the shop with the receipt of his/her shopping experience: it proves the payment of course, but it also indicates your ID number to follow the production of your shoes and to ask for your feet's data and eventually change them in the future. The finished shoe will be sent directly at client's house or to the shop where the client can try on once more the shoes.

Is the shoe the only example of production paradox? No, there are many and in different sectors. Research has shown that, for example, in the textile industry, around 40% of the products are unsold. The fashion industry is particularly touched by this problem.

5.1 Further Change Through the Paradigm: From the "Consumer-Product" to the "Consumer-Producer" Relationship

Along with the production paradigm change, there is another paradigm that is changing, and it is also related to production but looking from a different hbox-perspective.

Looking above at Fig. 2, there is a diagonal line crossing the timeline. This is the divider between the market-push and market-pull perspective. This definition is purely based on economic perspective because the economic reason has been the dominant factor in the human society starting in the Renaissance period in Italy [18].

However, if we want to explain in a different way this dividing line, we should look what history is telling us. Before the Renaissance, the social reason was the dominant factor, but in the Renaissance the economy has started its "emancipation" with the first trader and merchants. Then in the sixteenth, seventeenth, and eighteenth centuries, the economy starts to develop in an autonomous way, and the merchants were devoted to organize the work of other peoples. At the beginning of the nineteenth century, there is an "inversion" and the economic reason beginnings to take over the social one. In this period, the first industrial revolution takes place but in fact it is not, as normally it is presented, just a technological revolution but a social revolution: the people understand they can sell their work/effort and time for a salary, and they become dependent of the economic reason.

The economic power starts its domination. There are several other steps in the development and success of the "economic reason" and its greater and greater dominance on the "social reason." It is not our purpose to discuss in detail this large phenomenon presented in thousands of books, but we want to reach up to the contemporary time because it is when the worst results of the chain reaction is seen and come into our interest. Just a small remark: even the terminology has taken a new definition through the ages. For example, the word "company" comes from the Latin "cum panis" that means "sharing the bread": we have become so detached from the original idea.

Actually the "economic science" has developed in such a way that it creates more and more needs in the people, not only in the normal consumer goods (shoes, clothes, etc.) but also for other products like cars and even in domains where the economy was previously not involved like cinema, arts, music, etc. And in order to respond to the increased needs of the market, new technologies and methodologies are developed like automation, robots but also mass production, lean manufacturing, etc. The system is so integrated that in its research for greater and greater efficiency, it also creates enormous wastes that we can consider even insane. Because of the efficiency, it is only economic, and therefore if a waste is justified, then it is considered beneficial. The most absurd development of this insane path is the speculation on future profits or "the futures" that brings the collapse of 2008.

But finally it seems that there are some seeds for the breaking down of the reaction chain and bring back some value to the "social reason." We should here warn however that we do not think in terms of "social revolution" like Marxism or communism because we have seen how the societies based on these ideas or ideals have invariably developed and become subjected to the "economic reason" and the last example is China that does not need any comments.

We are interested instead to try to find out how it is possible to change the way we see the consumer and the product. In the mass production paradigm, the client or the consumer sees the finished product in the shop or in the department store or, more and more, on a screen during the online shopping. But then the product is finished, and there is no possibility to adapt it according to the own desire or needs, and there is no relationship between the client and the mass producer.

In the mass-customized paradigm, this changes: the consumer has a direct relationship with the producer. The consumer becomes part of the process to design and produce the object he/she wants. The "relationship" between the producer and the consumer becomes the most important aspect in the transaction: the "social reason" is now taking over again, and a social relationship is established and not purely an "economic reason." This change of relationship has profound consequences also on other aspects like reduction of waste (not trash!), less energy required, less pollution but also, and probably more important, there is finally a breaking down of the "economic chain" and its dominance on our market first and moreover on the entire society.

6 Conclusion

We live in a time in which it's clear the paradigm of mass production is not working anymore in a sustainable manner, but it continues to be dominant, thanks to the control of a broader standard that is the hegemony of the economy on cultural, economic, social, ecological, etc. reasons.

In Billeter's essay [18] there are various statements that he has brought from his research and experience: we need to be open-minded to a plurality of paradigms. The power of the economic reason is that it stands out as THE ONLY paradigm that the society wants to sponsor.

Using scientific methodology, experience and research as presented in this paper, we can develop other and new paradigms (like the greener mass customization). Billeter writes in his book about China [18]: "I am in favor of a pluralism that I would describe as absolute or radical because it is subject to any higher order and it is not supposed to be absorbed into a larger reality. I consider this kind of pluralism that Europe has as a most valuable product. I liked China, I studied its traditions for fifty years, but I have not found this plurality. After this adventure, I feel to be European for this reason: the plurality of persons, works or cities." Furthermore we would add plurality of paradigms and their consequences on an individual, animal, plant, and even mineral and not only consider the impact of economic reason on the planet.

The paper proposes an innovative view on a complex concept that the society has so hardly stigmatized to create a paradox. It is necessary to have a critical approach starting from a scientific measurable data.

The mass production paradigm is a very efficient way to make products and push them on the market at prices that are affordable to a large part of the world population because they answer to real clients' needs. But mass production is just a mean of a larger paradigm that is based mainly and almost only on the economic reason, and this brings not only efficiency in price but also big waste, pollution, and social conflicts (even among the nations to find and conquer primary natural resources).

The mass customization paradigm can maintain the advantages of the "mass" production but reducing considerably the disadvantages. The waste in terms of energy and natural resources are considerably reduced, and the same for the pollution.

Finally, we can restore the most important reason for the human society, that is, the "social relationship" between the producer and the consumer where the product is not just a mere economic transaction but a way to establish a relationship.

Today we have the technologies to make the change and go from mass production to mass customization:

- Virtual reality for design
- Robotics and automation for production
- 3D printing for manufacturing
- Smart factory or factory 4.0 for logistic and control
- Smart city for integration

What do we miss then to make the change?

- Vision
- Political willingness
- Education
- Cooperation between sustainability stakeholders

If the vision will be accepted with political willingness to implement it, education will be the primary tool for the success of the new society based again on "social reason" and not exclusively on "economic reason." Only by educating, from the Latin e-ducere or take out from the new generations and not pushing with simply notions, it is possible to demonstrate the contradictions of the society today and to show which are the ways to change. Give the young generation the ideas and systemic way to see the world in which they live, and they will be able to implement the new society through one of the sustainable development goals: "Inclusive and sustainable industrial development [. . .] for rapid and sustained increases in living standards for all people [9]."

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Mass Customization and Environmental Sustainability: A Large-Scale Empirical Study

Enrico Sandrin, Alessio Trentin, and Cipriano Forza

Abstract A growing number of firms nowadays need to combine mass customization (MC) with environmental sustainability management (EM). However, the research on the synergies or trade-offs between MC and EM is still in its infancy. Furthermore, the few findings available in the literature are partly conflicting: some studies suggest that MC and EM may be synergistic, while others raise concerns on the environmental sustainability of MC. This paper contributes to this debate by presenting the results of the first, large-scale, empirical test of some of the synergies suggested by prior research. Our results support the existence of two types of synergies between the MC capability of parts commonalization and the EM capability of product stewardship. One type of synergy is explained by the fact that parts commonalization capability reinforces the positive effect of product stewardship capability on environmental performance (interaction-based synergy). The other type is explained by the fact that both these organization capabilities require the same routines of cross-functional integration (shared routine-based synergy). Besides enriching the debate on the relationships between MC and EM, our results also contribute to the broader discussion on the compatibility between economic and environmental sustainability dimensions.

Keywords Mass customization · Environmental sustainability · Commonality · Product stewardship · Cross-functional integration · Moderation · Survey research

1 Introduction

Both mass customization and environmental sustainability management are increasingly relevant to manufacturing firms [1, 2]. Mass customization (MC) denotes the ability of a firm to fulfill each customer's idiosyncratic needs without substantial

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trade-offs in cost, delivery, and quality [3–5]. Environmental sustainability management (EM) means integrating environmental sustainability principles into businesses [6].

While more and more companies face the twofold challenge of combining MC and EM [7], the existing literature mostly focuses on either MC [e.g., 8] or EM [e.g., 9]. Only recently has research begun to investigate the possible relationships between EM and MC. In particular, some authors have suggested that MC brings not only economic advantages but also environmental benefits [e.g., 10, 11]. Other authors have conversely raised concerns on the environmental sustainability of MC [e.g., 12].

In summary, when it comes to the relationships between EM and MC, prior research is very limited, especially as far as empirical studies are concerned [13], and its results are at least partly conflicting. In view of this research gap and these mixed findings, and considering that both MC and EM require specific organizational capabilities [14, 15], the present paper uses secondary data to test, on a large scale, the existence of synergies between the MC capability of parts commonalization and the EM capability of product stewardship.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature, while Sect. 3 develops the research hypotheses. Section 4 presents the method we used to test these hypotheses, while Sect. 5 reports the analysis results. Finally, Sect. 6 discusses the theoretical and managerial implications of the study, as well as its limitations and directions for future research.

2 Literature Review

2.1 Organizational Capabilities and Routines

Organizational performance, including environmental performance, can be seen as the result of organizational capabilities [e.g., 16]. These latter are often regarded in the literature as combinations of organizational routines, which are repetitive patterns of interdependent organizational actions [17]. In line with this view, an organizational capability is defined here as the organizational knowledge of how to repeatedly organize a number of inputs in order for the organization to obtain a desired output [18]. It is worth noting that this conceptualization of organizational capabilities, which is typical of the strategic management literature, differs from the conceptualization that is common in the operations strategy research. The latter stream of the literature regards capabilities as “business unit’s intended or realized competitive performance or operational strengths” [19: 730], thus focusing on the outcome a capability is supposed to enable rather than on the “means” to achieve that outcome [19].

2.2 *Environmental Sustainability Management and Its Enabling Capabilities*

Companies nowadays are expected to be responsible not only to their shareholders, but to society in general, by matching their economic and financial results with minimization of ecological footprint and increased attention to social aspects [20]. This attention to the well-being of society is reflected in the concept of social responsibility, defined as “discretionary corporate activity intended to further social welfare” [21: 795]. Corporate social responsibility is a theme that has gained large prominence in academic research in recent times; in particular, large attention has been paid to the preservation of the environment [22]. As previously mentioned, the integration of environmental sustainability principles into a company’s business is known in literature as environmental sustainability management (EM), and it is a concept that emerged in the 1990s [23]. It was during that decade that the term “eco-efficiency” was coined and organizations started to look for innovative ways to reduce materials use, to utilize renewable energy, etc. [24].

In recent years, management scholars have become particularly interested in the organizational capabilities underlying EM. Hart [25], in his seminal paper, introduced this theme in the strategic management literature by proposing three EM capabilities: “product stewardship,” “pollution prevention,” and “sustainable development.” A few subsequent studies in the same body of literature have proposed additional capabilities a firm should develop and deploy for EM. Some of these capabilities have a clear environmental purpose stated in their definitions, such as Aragón-Correa and Sharma’s [26] “proactive environmental strategy.” Others, though supporting EM, do not have such an explicit environmental purpose in their definitions and, therefore, can be seen as complementary assets for EM capabilities rather than as EM capabilities. This is the case, for example, of Sharma and Vredenburg’s [27] “stakeholder integration” capability, that is, the capacity to develop trust-based collaborative relationships with stakeholders.

More recently, EM capabilities have become a topic of interest to the operations and supply chain management literature as well. By focusing on the supplier network, Bowen et al. [28] proposed the capability of “green supply.” Instead, by looking at downstream supply chain operations, Miemczyk [29] identified 13 organizational capabilities for end-of-life product recovery, and Wong et al. [30] focused on the capacity, called “process stewardship,” of efficiently using materials and resources not only in end-of-life operations but also in the manufacturing and distribution processes. With a holistic view of the supply chain, Bremmers et al. [31] proposed the capability of “environmental information and communication,” which is the capacity to communicate the firm’s environmental performance to a variety of external stakeholders and to exchange information in the entire supply network to reduce the product life cycle environmental impact. An even more comprehensive perspective was finally adopted by Lee and Klassen [15], who proposed the following five EM capabilities, covering also organization design aspects: “product environmental management,” “process environmental management,” “organization environmental management,” “supply chain environmental management,” and “relationship environmental management.”

2.3 Mass Customization and Its Enabling Capabilities

As compared to the research stream on EM capabilities, the one on MC capabilities is more recent and relatively underdeveloped. The first authors to use the term “capability” in conjunction with the tem “mass customization” were Tu et al. [32], who defined MC capability as an organization’s ability to produce differentiated products without sacrificing manufacturing costs while also being able to quickly deliver those products to individual customers. Similar to the manufacturing capabilities studied in the operations management literature, Tu et al.’s [32] MC capability is conceptualized as a competitive performance, rather than as a combination of routines and resources that contribute to determine such performance [19].

Conversely, Zipkin [33] identified three MC capabilities that are more in line with the “capabilities as routine bundles” view that is typical of the strategic management literature: “elicitation,” “process flexibility,” and “logistics.” These capabilities are related to the one proposed by Tu et al. [32] in that they can be thought as the means that a company needs to employ to achieve Tu et al.’s [32] MC capability.

Subsequently, Salvador et al. [14, 34], elaborating on Zipkin’s [33] capabilities, proposed another three capabilities that support the organizational movement toward MC: “choice navigation,” “solution space development,” and “robust process design.” “Choice navigation,” which requires Zipkin’s [33] “elicitation,” is the capacity to minimize the effort required of a customer to identify, within the company’s solution space, the product that best satisfies his/her needs. “Solution space development,” which too requires Zipkin’s [33] “elicitation,” is the capacity to identify the product attributes along which customers’ needs diverge. Finally, “robust process design,” which includes Zipkin’s [33] “process flexibility,” is the capacity to reuse or recombine existing organizational and value chain resources to fulfill a stream of differentiated customer’s needs.

More recently, Trentin et al. [35] added to this emerging debate in two ways. First, they proposed another two MC capabilities that do not overlap with the ones defined by Zipkin [33] and Salvador et al. [14], that is, “MC integration into strategic planning” capability and “continuous improvement for MC” capability. Second, they pointed out that Salvador et al.’s [14] “robust process design” capability encompasses three, not necessarily co-varying, lower-level capabilities, that is, “parts commonalization,” “process standardization,” and “suppliers flexibilization.”

3 Hypothesis Development

3.1 Product Stewardship and Environmental Performance

Product stewardship capability is an EM capability, defined as the capacity of a manufacturing organization to design new products with minimal life cycle environmental impact [25]. Product stewardship entails integrating the "voice of environment" into the new product development process and is one of the three fundamental capabilities identified by Hart [25] in his seminal work on environmental strategies.

Product stewardship capability improves environmental performance in several manners, for example, by minimizing the use of nonrenewable resources, by avoiding the use of toxic materials, by facilitating the reuse or recycling of products, and by minimizing the environmental impact of the entire supplier system [25]. Accordingly, the following research hypothesis is proposed.

H1 Product stewardship capability has a positive effect on environmental performance.

3.2 Parts Commonalization and Environmental Performance

Parts commonalization capability is one of the MC capabilities proposed by prior research. It is defined as the capacity of a discrete manufacturing organization to reuse the same product parts to fulfill a stream of differentiated customer needs [35].

Parts commonalization capability may have both positive and negative effects on environmental performance. The positive effects are due to reduced inventory and lower obsolescence of product components as well as to fewer manufacturing changeovers. Parts commonalization reduces the inventory of product parts by virtue of the so-called risk pooling effect [36]. In addition, the use of common parts across several products and among product generations reduces the risk of parts obsolescence [36]. Finally, parts commonalization decreases the number of manufacturing setups, which depends on the number of different parts and products manufactured by a firm, by decreasing the variety of components [36]. Reduced inventory, lower obsolescence of product parts, and fewer changeovers all imply that less environmental resources are consumed, thus enhancing environmental performance.

However, parts commonalization can also have negative effects on environmental performance. This happens when parts commonalization leads to the use of parts with excess capability for particular applications [37]. The production of these over-designed parts requires higher consumption of resources, thus decreasing environmental performance.

Given that the existing literature supports both the view that parts commonalization capability improves environmental performance and the opposite view that a higher degree of parts commonality has detrimental effects on environmental performance, we decided not to propose a specific research hypothesis on the effect of parts commonalization capability on environmental performance.

3.3 Synergies Between Parts Commonalization and Product Stewardship

The existing literature proposes two explanations for the existence of synergies between the MC capability of parts commonalization and the EM capability of product stewardship. One explanation revolves around the notion of interaction effect, while the other relies on the idea that the same organizational routine can help develop distinct organizational capabilities.

Interaction-Based Synergy A distinguishing feature of discrete manufacturing organizations is the fact that their products are composed of separate components. In such a context, the development of product stewardship capability leads to designing product components with reduced life cycle environmental impact, such as components with more recyclable materials. If a company has previously developed the capacity to reuse the same component parts to fulfill heterogeneous customer needs, fewer component parts will be needed to create a certain variety of products, and common components will be used in larger volumes. Consequently, the environmental benefits of designing a component with reduced life cycle environmental impact will be greater if the component is shared across different products [35]. Accordingly, the following research hypothesis is proposed.

H2 The positive effect of product stewardship capability on environmental performance increases as parts commonalization capability increases.

Shared Routine-Based Synergy Both parts commonalization and product stewardship capabilities require cross-functional integration [35]. Cross-functional integration is a process of interaction and collaboration in which an organization's functional departments exchange information and work together in a cooperative manner to arrive at mutually acceptable outcomes [38, 39].

Cross-functional integration facilitates parts commonalization by easing resolution of the complex trade-offs that parts standardization decisions may involve (e.g., common components can lower manufacturing costs but also hinder the ability to extract price premiums through product differentiation) [40]. At the same time, cross-functional integration facilitates product stewardship because every step of the value chain, from raw material procurement up to product disposal, must be taken into account to develop new products with minimal life cycle environmental impact [25]. Based on the above arguments, the following research hypothesis is proposed.

H3 Parts commonalization capability and product stewardship capability are positively correlated.

4 Method

4.1 Data Description

The data used for the empirical analyses are part of the fourth round of the High Performance Manufacturing (HPM) project. The sample used includes 304 mid- to large-sized manufacturing plants from 3 industries (machinery, electronics, and transportation equipment) and 13 countries (Brazil, China, Taiwan, Japan, Korea, Vietnam, Germany, the UK, Finland, Sweden, Italy, Spain, and Israel). Twelve different questionnaires were developed by HPM researchers and were directed to as many different respondent categories to obtain information from the respondents who were most knowledgeable. In each country, HPM researchers randomly selected a list of plants in each industry and, to maximize response rate, contacted the managers of each plant to solicit the plant's participation. In return for participation, each plant received a detailed report comparing its manufacturing operations profile to those of other plants in its industry. Owing to missing responses to the survey items used in this study, 66 plants were removed using listwise deletion.

4.2 Measures

Parts commonalization capability, product stewardship capability, and environmental performance were measured using multi-item five-point scales, which are reported in Table 1.

5 Results

Data analysis was performed via partial least squares structural equation modeling (PLS-SEM). SmartPLS 2.0.M3 was used to evaluate the measurement model and the structural model. A bootstrapping estimation procedure, in which 5000 random observation samples were generated from the original data set, was used to analyze the significance of scale factor loadings in the measurement model and the significance of path coefficients in the structural model. Before launching the

Table 1 Measurement items and PLS-SEM results for the measurement model

Measurement item	Std path load
Parts commonalization capability (NPD)* – CR = 0.81, AVE = 0.68 5-point Likert scale (1 = strongly disagree, …, 5 = strongly agree)	
PCC1: We have defined product platforms as a basis for future product variety and options	0.70***
PCC2: Our products are designed to use many common modules	0.94***
Product stewardship capability (EA)* – CR = 0.79, AVE = 0.56 Please indicate the degree to which your plant is engaged in the following initiatives/practices: (1 = no extent whatsoever, …, 5 = very great extent)	
PSC1: Life cycle analysis of the "cradle to grave" environmental impact of materials/products	0.77***
PSC2: Environmentally preferable packaging for the products that you produce (recycled content, less volume, reusable packaging)	0.65***
PSC3: Substituting environmental preferable direct materials or supplies for harmful or nonrenewable ones	0.81***
Environmental performance (EA)* – CR = 0.91, AVE = 0.78 How does your plant compare to others in your global industry on: (1 = much worse, …, 5 = much better)	
EP1: Raw materials consumption	0.88***
EP2: Energy consumption	0.92***
EP3: Water consumption	0.84***

*Respondent category (*NPD* new product development, *EA* environmental affairs)
***$p < 0.001$

PLS-SEM estimation, a construct that modeled the interaction effect between parts commonalization and product stewardship was generated by using the SmartPLS product indicator approach [41].

The assessment of the measurement model properties showed acceptable unidimensionality, convergent validity, and reliability for all our multi-item measurement scales (Table 1). Furthermore, Fornell and Larcker's [42] procedure indicated good discriminant validity for such scales. Finally, criterion validity for the environmental performance construct was proved by linking this construct with another construct, reflected by the item "overall environmental performance" and by the positive and highly significant ($p < 0.001$) relationship between these two constructs.

The assessment of the structural model provided the structural model path coefficients and their statistical significance reported in Fig. 1.

As shown by the path coefficients, the impact of parts commonalization capability on environmental performance is not statistically significant ($p > 0.10$). Conversely, the path coefficient from product stewardship capability to environmental performance is positive and statistically significant ($p < 0.001$), thus supporting hypothesis H1. Likewise, the path coefficient from the interaction construct (PCC × PSC) to environmental performance is positive and statistically significant ($p < 0.01$), thus supporting hypothesis H2.

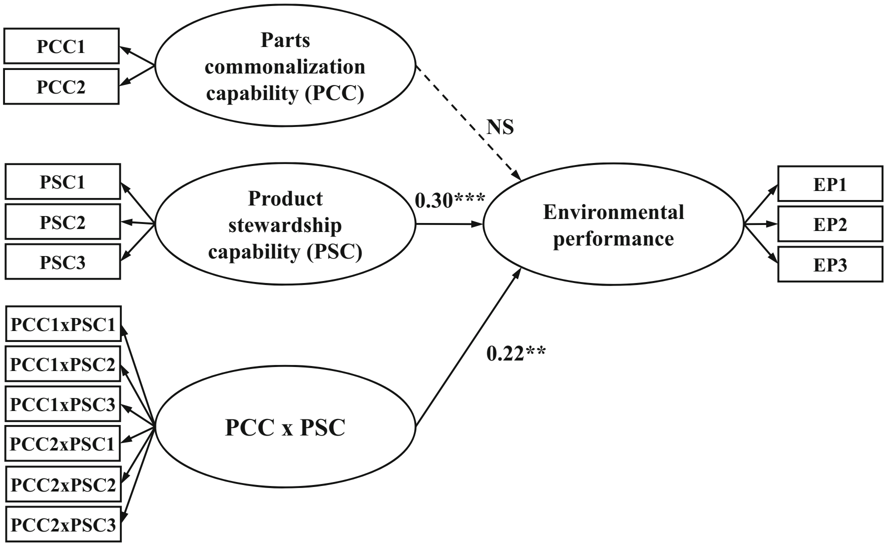

Fig. 1 PLS-SEM structural model estimates (NS $p > 0.10$; $^{**}p < 0.01$; $^{***}p < 0.001$)

The predictive power of the structural model was assessed by the coefficient of determination (R^2), according to which the model explains 22% of the variance in the environmental performance [41, 43]. The predictive relevance of the model was demonstrated by the value, greater than zero, of the Stone-Geisser's Q^2 for the environmental performance [41, 43].

The interaction between parts commonalization and product stewardship capabilities was further investigated using the Aiken and West's [44] procedure by conducting moderated multiple regression analysis. In order to perform the regression analysis, the scores of the PLS-SEM latent variables were used as the values for the variables of interests. The regression of environmental performance on product stewardship capability was examined at each of three particular values of parts commonalization capability (i.e., its mean value, low value at one standard deviation below its mean, and high value at one standard deviation above its mean). The corresponding three simple effect slopes showed that as parts commonalization capability moves from low to high, slope increases while remaining highly significant, thus showing that the positive effect of product stewardship capability on environmental performance is positively moderated by parts commonalization capability.

Hypothesis H3 was tested using the Pearson correlation coefficient between the latent variable scores of parts commonalization capability and product stewardship capability. The Pearson correlation coefficient is positive (0.11) and (marginally) significant at $p < 0.10$ (2-tailed), thus providing weak support to H3.

6 Conclusions

The present paper adds to the existing literature in several ways. The first contribution stems from the fact that prior research findings on the relationships between MC and EM has mostly relied on conceptual research and exploratory case studies designed to investigate a hitherto unstudied area [7, 13]. As the research matures, however, there is an opportunity of designing explanatory surveys that verify theoretical relationships in larger populations [45]. To our knowledge, this is the first study to empirically test, on a large scale, the existence of the synergic effects that Trentin et al. [35] posited to exist between the MC capability of parts commonalization and the EM capability of product stewardship based on a single, longitudinal case study involving a machinery manufacturer. The results of the tests performed in our sample of 238 mid- to large-sized manufacturing plants from 3 industries and 13 countries support the existence of these synergies. This finding enriches the emerging debate on the relationships between MC and EM not only by strengthening the external validity of two of Trentin et al.'s [35] propositions. This finding also corroborates the idea that MC and EM are compatible strategies, in opposition to the concerns on the environmental sustainability of MC that other studies have raised.

A second contribution can be noticed if one takes into account that MC is a fundamental condition for the economic sustainability of a manufacturing firm that faces highly heterogeneous demand and intense competition [35]. This observation implies that the results of this paper also contribute to the broader discussion on the compatibility between the different dimensions of sustainability. The existing literature on this topic has been evolving following two main different paradigms. The mainstream one is the win-win paradigm, according to which economic, environmental, and social sustainability can be achieved simultaneously [46]. According to this view, a positive association exists between EM initiatives, with their environmental performance improvement outcomes and economic performance [e.g., 47–49]. Conversely, the second paradigm, known as the trade-off paradigm, argues that sustainable development can only be achieved if a firm accepts a compromise between the three sustainability dimensions, which are in conflict which each other [46]. According to this view, EM initiatives do not come for free and may deteriorate the firm's economic performance [e.g., 50, 51]. The present paper adds to this debate by providing additional, large-scale, empirical support to the win-win paradigm.

A third contribution emerges if one interprets the results of this study through the concept of complementary asset for a certain strategy, defined as any organizational element that increases the value of that strategy [52, 53]. Previous studies have identified several complementary assets for an EM strategy, such as total quality management processes [25, 54, 55], the organizational capabilities to generate and successfully implement innovations concerning production processes [56], and acceptance of change by organizational members [57]. The present paper adds parts commonalization capability to this set of complementary assets for

EM by providing strong support to hypothesis that the MC capability of parts commonalization amplifies the environmental performance benefits of an EM strategy that promotes the development of product stewardship capability. At the same time, the weak support we found for the hypothesis that parts commonalization and product stewardship capabilities positively co-vary suggests that not only is parts commonalization capability a complementary asset for EM, but also product stewardship capability can be a complementary asset for MC.

A fourth contribution of this study lies in its finding that parts commonalization capability does not affect environmental performance directly. This result is somehow unsurprising if one considers that prior research has argued both in favor of the positive effect of parts commonalization capability on environmental performance and in support of its negative impact on the same performance dimension. What our findings suggest is that the positive effects tend to counterbalance the negative ones. However, this is just a conjecture, which deserves additional research.

From a practical standpoint, the results of this study are of interest for at least two reasons. First, they provide large-scale, empirical support for the idea that improving cross-functional integration pays off both in terms of MC and in terms of EM, thus helping companies faced with highly heterogeneous demand and intense competition in improving both economic and environmental sustainability. Second, this study shows that, in a discrete manufacturing environment, a high degree of component commonality acts as a multiplier of the environmental performance benefits of the capacity to design products and, hence, product components with reduced life cycle environmental impact.

As with any other piece of research, this study is not without limitations, which might be addressed in future research. The cross-sectional nature of the dataset limits our ability to explore the causal relationships between the constructs of interest in this research. In addition, our cross-sectional dataset does not allow for testing the existence of the path dependence that, according to prior research, explains the positive interaction effect of parts commonalization and product stewardship on environmental performance. Testing this explanation will require collecting longitudinal data. Another limitation of this study is its use of secondary data. The measures in the HPM dataset were not designed for investigating the links between MC capabilities and EM capabilities in the first place. Therefore, future studies could be devoted to gathering primary data that allow for empirically testing other relationships, involving other MC capabilities and other EM capabilities than the two examined in this research. It must be acknowledged, finally, that the positive impact of product stewardship capability on environmental performance is somehow an unsurprising result, since the items used to measure this capability capture a number of actions a company needs to take to reduce the life cycle environmental impact of its products. However, these measurement items are consistent with the strategic management view of organizational capabilities as "means" or pathways to achieve a certain outcome [19]. Furthermore, the analyses we performed showed good discriminant validity between the constructs of product stewardship and environmental performance. At any rate, the issue of the impact of product stewardship on environmental performance is not central to the aims of this research, which focuses on synergies between MC and EM capabilities. This impact was included in our research model for the purpose of testing the existence of an interaction-based synergy between product stewardship and parts commonalization capabilities.

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Opportunities and Challenges of Product-Service Systems for Sustainable Mass Customization: A Case Study on Televisions

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Abstract The diversification of products that adapt to specific customer needs has been a growing competitive advantage for many businesses. As customers become more self-aware and demanding in their buying preferences, mass customization (MC) is experiencing a considerable growth. In the light of growing trends towards sustainable consumption, MC can become a strong drive for the implementation of sustainable products and services. Product-service systems (PSS) exhibit attributes that can be harmonized with several features of MC, for instance, the enhanced communication mechanisms between customer and businesses. Hence, in this paper, we explore the potential conjunctions of the PSS and MC business models from a sustainable point of view. More specifically, we describe the opportunities and challenges of a sustainable product-service system (S-PSS) with focus on environmental impacts and how these services can influence the environmental performance of a mass-customized product. A case study is presented that describes the assessment approach that is based on the life cycle assessment (LCA) method on three comparative scenarios for sustainable product-service systems for a television. The scenarios selected are take-back service, extended warranty and changing to a renewable energy provider. Part of the analysis and results of this study are based on the research project SMC-EXCEL, a joint research programme supported by ECO-INNOVERA (funded by BAFU (Switzerland), BMBF (Germany) and TUBITAK (Turkey)).

Keywords Life cycle assessment (LCA) · Sustainable mass customization (MC) · Product-service systems (PSS) · Sustainable product-service systems · Television

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1 Introduction

The increasing competitive nature of the consumer electronic market is leading businesses to seek for new ways of differentiating themselves from competitors. With that purpose in mind, mass customization (MC) has emerged as an alternative to the mass production (MP) model as MC aims for the “technologies and systems to deliver goods and services that meet individual customers’ needs with near mass production efficiency” [1]. By choosing customizable products as the main selling point, the MC model builds on a customer centric strategy, which implies that demands and wishes of each customer are placed in the centre of the value creation for the enterprise [2, 46]. Hence, the success factor of MC is highly dependent on recognizing and adopting prevalent trends that customer segments of the MC business are manifesting. One of those growing trends today is the increasing concern of consumers on environmental and social issues that can lead to a higher demand for sustainable products and for social and environmental business practices. Furthermore, in the views of globalization, digitalization and economic integration, consumers that adopt buying behaviours for a more sustainable lifestyle present a much larger group which has gained greater leverage on the current market dynamics [3]. For these reasons, businesses in development such as the MC enterprises can benefit from reacting and anticipating to the potential consumers who opt for sustainable business practices and products. Based on the premise that sustainability can be a major success factor for MC, this study explores the development of a sustainable MC business model through the application of product-service systems (PSS), looking at sustainability mainly in terms of the environmental performance of the business model. We aim to identify the aspects that act in accord within both the MC and PSS models, providing opportunities for correlation as well as obstacles that can arise from the integration of these types of business models.

To that end, we follow on from the conclusions concerning PSS as a lever for the environmental sustainability potential of MC as presented by Hankammer and Steiner (2015) [4] – i.e. with the testing of three different MC-based PSS scenarios for televisions, as part of the SMC-EXCEL project. The process and results are discussed in more detail in Sect. 5 of this paper. The analysis of environmental impacts was based on the life cycle assessment (LCA) methodology. As the name implies, LCA takes a life cycle approach to assess the product environmental impacts and quantifies those in terms of environmental characterization factors such as global warming potential, eutrophication, ecotoxicity, etc. LCA is a comprehensive and reliable tool with wide recognition and application within environmental science communities, industry and policy makers.

2 Mass Customization and Sustainability

A commonly known definition of MC is provided by M. Tseng and J. Jiao, who state that MC “is the production of goods and services that meet individual customers’ needs with near mass production efficiency” [1]. More specifically, MC can be understood as a “paradox-breaking manufacturing reality that combines the unique products of craft manufacturing with the cost-efficient manufacturing methods of mass production” [5]. In craft manufacturing, product prices are high, and the production process takes considerably more time than in mass production processes [6]. In contrast, mass production focuses on efficiency. As MC aims for a hybrid strategy that combines mass production and craft production, its success depends on several factors such as stability and control of all processes [7], as well as efficiency through economies of scale and highly economical but also flexible manufacturing systems [8]. In contrast to mass producers, mass customizers create product variety in combination with low prices to meet individual customer needs [7, 9].

Sustainable benefits that can be achieved through mass customization are widely discussed among practitioners and researchers. Some argue that MC could reduce overproduction, resource consumption and enable more efficient models of reuse and recycling [4, 10]. Others ponder that the diversification of products would reduce the efficiency of production and supply chain processes as production cycles, assembly lines and logistics of transportation become more complex [10]. The negative impact on sustainability performance could emerge from a greater use of resources, from inefficient transportation methods or from the modular features of the product that can lead to higher energy and material consumption [10]. Porabdolloahin et al. [11] find that the mass customization model can present both positive and negative environmental impacts when compared to mass production. The study further explains that each of these factors is dependent on the specific MC approach that is chosen. Similarly, Bruno et al. [10] explain that MC is not either sustainable or unsustainable but has indeed the potential to contribute to sustainability.

Hence, there is no clear indication whether the MC model contributes with substantial environmental benefits or which type of MC model would result in a greater environmental performance [4]. However, as Medini et al. explore the operational aspects of sustainability and mass customization, they found that “companies seeking better sustainability performance are pushing forward the capacity of their production systems and supply chain towards more customized products” [12]. This may be taken as an indication that not only can sustainability act as a success factor on MC but also that sustainable business practice is more inherent to customization than it has been conjectured.

3 Product-Service Systems

According to Manzini and Vezzoli [13], a PSS is a strategic decision to move from designing and selling physical products to designing and selling systems of products and services that together can satisfy the user's needs. Several studies on PSS recognize three archetypes, which are classified as product-oriented, use-oriented and result-oriented PSS [14]. Product-oriented PSS is where the product offered is integrated with one or more services, while the product ownership remains with the customer. Product-oriented PSS are found, for instance, in warranty contracts, maintenance services or product installation. For the use-oriented variation, the product is the property of the producer, and the customer pays for a specific use. Common examples are leasing, renting or sharing services (e.g. for vehicles). The result-oriented PSS is when the customer pays the producer for a result as, for example, by outsourcing the work of moving furniture with a moving company. In the present study, we will focus only on the product-oriented PSS variant, in application to the mass customization of televisions – the main question examined being how different PSS strategies may affect the environmental performance of the same television product [15].

One of the first studies on PSS in the late 1990s by Goedkoop et al. [16] already envisioned the potential for environmental benefits as it concludes that there is a "positive perspective of PS systems for unlinking environmental pressure from economic growth". PSS have also been largely adopted by environmental strategists as they see its potential for the design field through dematerialization, efficient use of resources and consumer behavioural change [17, 49].

4 Product-Service Systems in Mass Customization

Hernandez et al. [15] argue that part of the competences required for PSS are innovation capacity, flexible operations and better communication skills. Regarding the last point, they state that "the rapid evolution of information and communication technologies (ICT) could give SMEs the competences required to develop sustainable PSS". The requirements regarding the use of ICTs could be equally applied to the MC model as it not only offers a product but also a buying experience that depends on a well-designed user interface, accessibility and the optimal number of customizable features vs. the time invested in customizing those features. Consequently, the MC business also involves a high level of dexterity with ICTs and E-commerce as its sales strategy is largely based on a configurator in the form of a software or web application [18].

The efficient use of communication technologies such as ICTs requires a well-founded communication strategy, a statement that is applicable for any business model that seeks to operate in today's digitalized market. For MC and PSS, however, the communication strategy is a more critical aspect within the business as the interaction with customers is intensified and becomes a predominant cost- and time-sensitive issue. The interaction with customers is strongly permeated by the co-creation process, where customers partially define features of the product or service that better fit their needs [18]. Thus, for both MC and PSS, to provide this added value to the product or service delivered, managing expectations from customers and the challenges that arise from the co-creation process is an important aspect to consider [19, 20, 50].

Furthermore, MC requires innovation capacity to balance the efficient use of resources through mass production methods with product variations that affect processes such as supply chain, design and assembly [18, 21]. Analogously, Hernandez et al. state that more efficient firms with higher innovation capacity and flexible operations are not only part of the benefits of sustainable PSS but also a requirement for its successful implementation [15]. Innovation capacity is thus another important factor that is shared among these two business models.

Finally, the modular design of a product is a key enabler for an efficient MC, and accordingly, modularity extends in form of flexible operations to the production processes and supply networks as well [10, 45, 47]. Likewise, standardization and modularity are also mentioned in studies on sustainable PSS as important factors to consider as they not only help to reduce process time and cost but also extend the durability and longevity of products [4, 17].

As several correlations can be identified for the MC and PSS requirements, we see it as a positive indication that PSS could be harmonically integrated within the MC business model. Goedkoop et al. [15] described, in 1999, MC as one of the major trends matching the PSS concept explaining that "for consumers it is the era of MC. End-users select commercial offers that suit their individual needs at lower-than-ever costs [. . .]. The client has come to regard product and service as two parts of the same commercial deal, thus blurring the borderline between product and service" [16].

Starting from the premise that MC and PSS can be efficiently coupled into one system, the next section aims for those features that relate to the sustainable potential that may rise through the SMC with integrated PSS solutions. In order to do so,

Figure 1 presents the key features in which MC and PSS reach consensus in their common requirements. These key features served as a guideline for the analysis on opportunities and challenges for sustainable MC through PSS. The analysis is supported by the insights obtained through the SMC-EXCEL project, in which the application of PSS through a sustainable MC pilot project was modelled and tested with users through a survey.

4.1 Opportunities for Sustainable Mass Customization Through PSS

The first key feature is communication strategy, which is outlined by a customer-business synergy of MC and PSS that requires a regular and reciprocal interaction between business and customer. This interaction is characterized by the co-creation

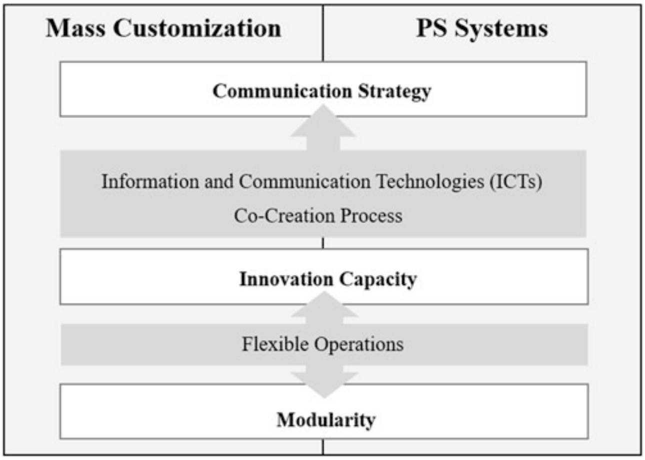

Fig. 1 Synergies between mass customization and product-service systems

process and enhanced through the application of ICTs [48]. As MC allows businesses to receive direct feedback from customers on their products or services, a stronger link between business and consumer can be created. Similarly, it is often in the nature of services to have a steady exchange of information with users (e.g. leasing, renting). In consequence, PSS has the capacity to influence and promote behavioural change of consumers for a more sustainable consumption [17]. Similarly, the SMC-EXCEL project results showed that consumers can be "nudged" to select a more sustainable product type by simply including more sustainable features in the presented configuration that is provided at the beginning of the configuration process.

The customer-business synergy can be further promoted through product stewardship, one of the main patterns characteristic to PSS and which is often related to its sustainable version known as extended producer responsibility (EPR). EPR can be defined as "…a resource and product-centred approach to environmental protection and social consideration, whereby producer, brand owner, consumers, corporations, communities, retailers, recyclers, local and national governmental agencies share in the responsibility for the life-cycle of a product (design, use and disposal)" [22]. By including PSS in MC, the elements that constitute EPR cannot only become inherent to the MC business strategy but even reinforce EPR as a sustainability concept. To explain, first it must be considered that both MC and PSS make use of the co-creation process, but it is mostly in the MC model that co-creation is a fundamental component, while for PSS it is not indispensable for its fundamental structure. Vasantha et al. even stated that "it is criticized that the PSS design methodology neglects the specification of the roles and responsibilities of the stakeholders co-designing PSS offerings, and that there is a low understanding of the uniqueness of this process and how to implement it in real time" [23].

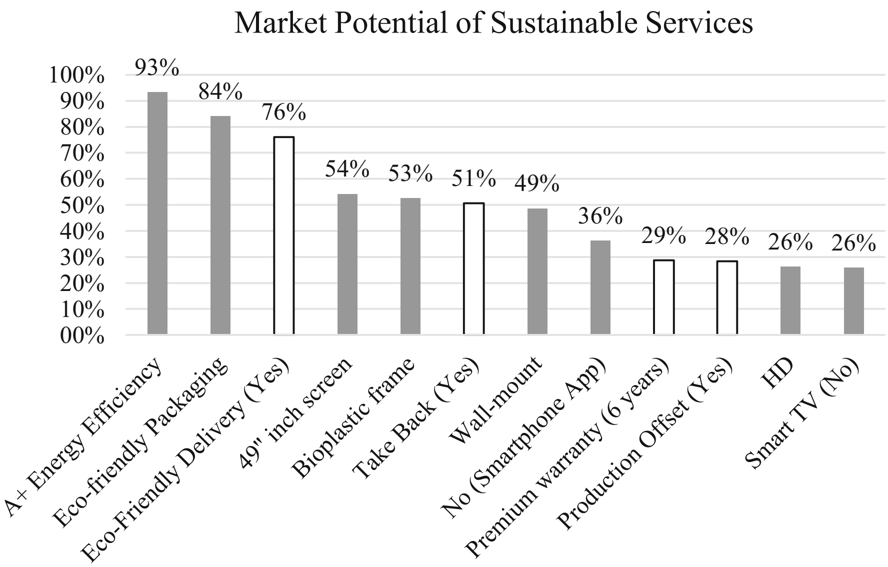

Fig. 2 Market potential of sustainable services [24]. (SMC-EXCEL project)

Imbedding EPR into the co-creation process could lead to the benefit that the responsibility and stewardship role assumed through EPR may distribute more evenly among business and consumers. Through co-creation, EPR generates a greater involvement of users at the decision level when industry sets the parameters for planning and market developments. The customer becomes less a subject but rather an actor in the market configuration and, consequently, he/she may also recognize more strongly their own role and responsibility for sustainable consumption. Supporting this theory, a survey conducted for the SMC-EXCEL project on a sustainable configurator confirmed that many users have a considerable interest in environmentally friendly product choices as well as sustainable PSS (marked in white bars) as shown in Fig. 2.

The innovation capacity in sustainable PSS is another important aspect when considering investments in new technology, materials or processes. The latter ones usually require medium to high investment and can imply cost critical effects on the business performance. Costs of sustainable services, however, can vary significantly depending on innovative structures that can be adopted in the MC business model. In the case of product-service systems that aim for the replacement of the product for its function (e.g. leasing or renting), the service implies often a change in the structural configuration of the business. It would mean replacing the entire business structure with a new one, which would most certainly require significant investment.

But other sustainable services that can be achieved through innovation and require a less radical change can be take-back services, extended warranty or software assistance services. In the case of televisions, for example, the producer may build into the TV software a reminder function that informs the consumer when to adjust the brightness levels of the TV (e.g. during winter time). The product is not dematerialized but rather assisted by the manufacturer so that the impacts of the product through its life cycles are diminished.

For the third category, modularity and opportunities can be found within certain PSS that are essentially not changing the product itself but rather the environmental impacts caused by the product at different life cycle stages. The environmental impacts related to the design of physical elements and processes in MC can be further transferred through PSS to the impacts of all the products life cycle phases. For instance, if the take-back service of products would be applied, the MC business needs to consider as well the end-of-life (EoL) scenario of the product as assembly lines may become also disassembly lines and transportation as well as agreements with third parties from the recycling industry must be arranged. Therefore, the modular feature of MC does not remain applicable only to its internal operations and prolongation to the supply chain level but also to those stages after sales such as the use and disposal phases.

As PSS have the potential of influencing the life cycle of products at post-production stages and even at multiple stages at the same time, it also has the potential to generate greater positive environmental impacts than single parts or components at a multisystem level. For example, if one component of the TV can be selected with either aluminium or bioplastic material, it causes a small impact compared to the overall product system. With a take-back service, however, all parts including the aluminium or bioplastic component can be recovered and enter a more efficient recycling stream. For small materials that are valuable but difficult to extract such as gold in PCBs, the take-back service applied by every manufacturer of TVs could theoretically also change the processes within the recycling industry as the distribution, disassembly and recovery channels become more efficient for this material. Finally, PSS can also be regarded as the enabler for creating closed-loop systems by applying circular economy principles (e.g. take-back) which would not be the case with the standard MC model. On that account, the MC model may not just reduce impacts by offering eco-design solutions but, in fact, offer products with virtually zero impact. A summary of opportunities for sustainable PSS in MC is shown in Fig. 3.

4.2 Challenges of Sustainable Mass Customization Through PSS

The challenge in the communication strategy is, primarily, to provide accurate environmental data on the product or service in a transparent and comprehensible way to customers. In the experience gained during the SMC-EXCEL project, the communication of sustainable features presented through the configurator to users revealed that disassociation and unfamiliarity to certain terms can hinder the understanding of sustainable features. As information such as kg CO2-equivalent

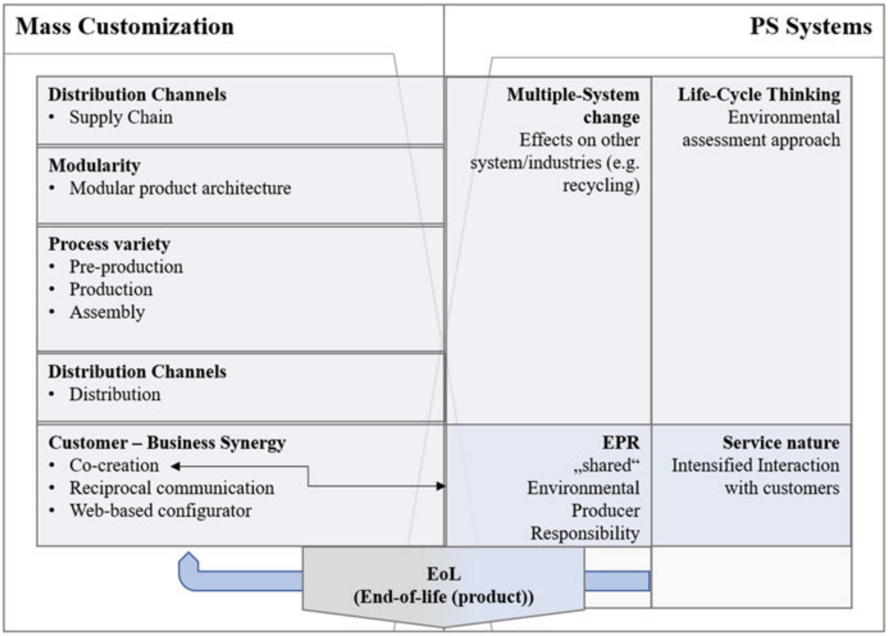

Fig. 3 Sustainable PSS and MC correlations

values or carbon offsetting is often not known, it is important that this information is translated in more familiar concepts. Furthermore, complementary information should be included for vague or unclear concepts (e.g. premium warranty). The placement of information or, more specifically, the user interface (UI) design is equally relevant for an efficient and fast absorption of information and co-relation between the features of the product and its environmental impact. Results further showed that the aspect of trustworthiness, as seen with the high ranking of the A+ energy efficiency label, can constitute a mayor decision factor in the selection process of users. The challenge in this regard may be the continuous upholding of a transparent image through a greater clarity in communication and certifiable results as, through an intensified communication, the risk of defamation or being labelled as "greenwashing" the product can be higher and cause greater repercussions to the business.

The innovative capacity is a latent requirement for both MC and PSS businesses as both seek a competitive advantage by differentiating themselves to other businesses models. However, innovation can bear significant challenges, in particular for SMEs. Zimmermann and Thomä categorized the barriers to innovation for SMEs in the following areas: (1) lack of organization and skills, (2) financial barriers and (3) bureaucratic barriers. Furthermore, they consider that the main barriers are generally attributed to high costs, uncertainty in economic success, lack of internal and external funding sources, lack of skilled workers, legal requirements and lack of market information and technological expertise [25]. Especially in regard to eco-innovation and sustainability, the lack of skilled workers [26], which may also be interpreted as skills obtained through collaborative research ventures, is found to be particularly important for the proper environmental assessment and communication of environmental information through the SMC business. To overcome these barriers, the SMC/project conclusions point out the importance of a well-designed environmental assessment methodology that is developed in collaboration with external experts and that may give indication on the environmental benefit obtained, such as through PSS, versus the investment that it may require.

As mass customization is characterized by its modular nature, it allows a great amount of possible combinations of elements and for which each requires a single data output in terms of price, weight and environmental impact. The SMC-EXCEL [24] project concluded that modularity in view of sustainable mass customization assigns a similar modular approach to sustainability features such as, for instance, the environmental assessment process. This type of modular system requires a flexible and combinatorial assessment method that allows for the addition and subtraction of independent components. For a classic LCA, it would require an analysis of each possible device combination, which is unfeasible to apply directly on MC. As such, for the SMC-EXCEL study, a matrix-based solution space was applied which enabled the independent definition of each data value for each component. These data values were broken down into their contribution to each life cycle phase of the component for the environmental assessment, allowing the needed flexibility when combining components and assessing sustainable PSS that affects one or several life cycle phases (e.g. transport) of a product.

The material and processes can be partitioned and categorized in separate product elements. In that way, data can be simplified, and the environmental assessment for each component becomes more feasible. By a standardization strategy, for example, in processes and design of modules, information on the impacts for each component may be used for more than one product, making the process of environmental assessment more efficient. In the case of product-service systems, the evaluation of the environmental performance of a variable product changes significantly. As mentioned before, PSS is not calculated as a separate component but, instead, on how it affects the system of the product in its entirety and across different life cycle stages. Through the SMC-EXCEL project, it was evident that the environmental assessment method selected for MC should, by any means, include a life cycle thinking approach allowing the more accurate calculation of impacts across the life cycle phases. The adaptation of LCA to this study is further described in chapter "Demand Engineering in Mass Customization Using a Data Driven Approach".

Besides the adaptation of a suitable environmental assessment method, another challenge related to the environmental assessment was the large amounts of data required, which can be a time- and cost-intensive process. Especially for external data, the business may encounter several barriers such as confidentiality of suppliers' information, location source of raw materials and know-how on business practices from other sectors such as the recycling industry. Consequently, the validity of data collected can be questionable as the data quality decreases if the supply chain information is inaccurate. Thus, as complications already exists in the initial stage of data collection, it is advisable for the business to receive counsel from experts that can filter and set up a structure for the most viable and accurate data compilation. Additionally, for the design and implementation of PSS, data plays a significant role for the environmental impact assessment. As PSS would require specific focus on the life cycle phases of the product for different components and materials, the problematic on gathering external data may be even more significant. These barriers could be overcome more easily if businesses within an industry collaborate, and with support of policy, set up data platforms and networks for a better exchange of information.

5 Case Study: Television and Sustainable PSS in Mass Customization

5.1 Literature Review on Environmental Impacts of Television

A few years ago, in 2010, the plasma technology television was considered as the leading and most important technology on the television market. A study conducted in that year describes the environmental impacts of a plasma display panel (PDP) television over its life cycle. The results indicate the importance of the energy mix during the use phase. With a fossil-based electricity mix, the phase dominates the whole life cycle of the television. Observing the production process, the electronic components have the biggest impact. Furthermore, the conclusion from this study was that recycling has a positive effect on the end-of-life phase. All in all, the responsible and long-term use of a television has a positive effect on associated environmental impacts [27].

Another study focussing on the impact of the use phase of a television found that "The use phase due to electricity consumption dominates the life cycle impacts in nearly all categories" [28]. Bakker et al. [29] think of this statement as a heuristic that can serve as a guideline for designers to implement eco-design in the early development process of products. Generally, the importance of eco-design is rising to face the increasing importance of sustainability. Since the lifespan of a television has significantly dropped since the year 2000, the focus on the use phase and therefore the energy consumption as the main cause for an environmental impact might no longer be applicable [29]. Also, technology of televisions has evolved so that the energy efficiency of a liquid crystal display (LCD) with the recent light emitting diode (LED) backlight is not comparable with, for example, cold cathode fluorescent lamp (CCFL) backlight technology. Bhakar et al. [30] compared different monitor technologies and, indeed, found that the use phase has a lower impact with LED than the manufacture phase. However, as the size of the screens has risen over the recent years, energy consumption is rising as well, even if the efficiency is improving [31]. The case study on the "Econova" concludes that focussing on both use phase and materials together with emphasizing recycling shall lead to a more sustainable television set. Hence, the impact of the production phase can become more relevant through higher energy and material efficiency and because more devices are produced and more material is needed. Due to the increased size of screens and impacts through energy consumption, however, the use phase can still be considered as one of the major environmental impact factors of televisions.

Besides the approach towards the use phase, the end-of-life phase is the main topic of a case study on LCD televisions published in 2015. This study identifies the PCBs as a hot spot for environmental relevance. With the evaluation of different recycling processes, the study underlines the importance of understanding the required process, especially, when no or insufficient reliable data is available. Hence, further work should focus on the estimation of the volumes of the end-of-life product in order to optimize the recycling process [32].

The state-of-the-art analysis of existing LCA studies on televisions highlights the importance of the production/manufacturing and the use phase, although the different technologies of televisions and assumptions on screen size, energy source or usage time can shift the paradigm on environmental impacts considerably between these two product phases.

5.2 *Life Cycle Assessment and Comparative Scenarios*

Consumers can easily influence the sustainability of a mass-customized product by their configuration choice. Therefore, three PSS scenarios for a sustainable business model were performed and analysed based on the findings of a television-configurator pilot that was conducted as part of the SMC-EXCEL project. These scenarios were calculated as a variation of a full-scale LCA study for a basic television set. The comparative PSS scenarios chosen were take-back service, premium warranty and the switch to a renewable energy provider. The scenarios were modelled with the open LCA software, using ecoinvent 3.2.

Scenario 1: Take-Back Service In the configuration process, the consumer has the option to select a "Take-back Service", i.e. where the consumers pay for the collection of an old television and delivery of a new one, indirectly assisting the manufacturer in increasing their recycling rate. The recycling rate of the television set in a standard situation (without take-back) is assumed to be 45%, based on information from the WEEE Directive where in 2016 a minimum of 45% of average electronic waste shall be collected [33]. Furthermore, Eurostat [34] data indicated that the collected and recycled amount of electrical and electronic equipment (EEE) in 2014 in Europe did not differ significantly, and hence, the same 45% rate of collection was used for the recycling rate. The take-back service can potentially increase the possibility for recycling – its rate is assumed to be increased to 75%. Television sets contain different valuable and rare-earth elements such as, gold,

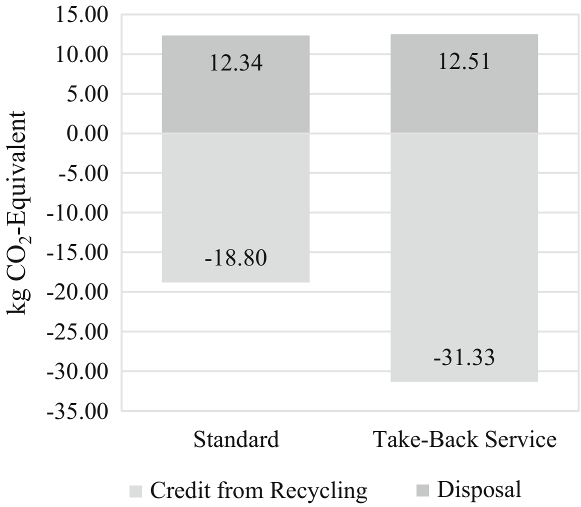

Fig. 4 Impact of take-back service on disposal phase compared to standard scenario. (CML (baseline) climate change – GWP 100)

silver, indium, yttrium and europium. Therefore, a higher recycling rate is an advantage for securing the supply of these critical materials. However, the recycling rate of these materials differs from under 1% (indium) up to over 50% (gold). Furthermore, more specific information on rare-earth elements are often restricted under trade secret [35]. Since especially some rare-earth elements today have only a very small recycling success, it is not realistic to calculate these materials with the higher recycling rate. Nevertheless, the scenarios show the possibilities if a higher recycling rate can be achieved. Furthermore, as no reliable rates were available, this was applied to all elements equally.

First, the environmental impact is compared focusing on the global warming potential over a time horizon of 100 years (GWP 100) using the impact assessment method CML (baseline). As the recycling rate has no direct impact on the production and use phase, only the disposal phase is illustrated in Fig. 4. The disposal phase is a rather small part of the whole life cycle of the television; therefore, relating to the overall environmental impact, the savings estimated was 2.2%.

In case of the recycling rate, the impacts resulting from the material used is of greater interest. The concerning impact category deals with the depletion of abiotic resources, e.g. metals and minerals [36]. The characterization factor is kg antimony equivalent. Antimony is a toxic semimetal, which is used for semiconductor devices like diodes [37] and therefore was used to represent rare materials required to manufacture a television. In comparison to the category climate change – GWP 100, the main contributors to this category are different, as illustrated in Fig. 5.

As shown in Fig. 5, the CO_2-emitting hot spot use phase is no significant contributor to the impact category "abiotic depletion: elements and ultimate reserves". More relevant are especially the power and main board and of smaller interest, the LCD display. For instance, the "integrated circuit production" is used in the main

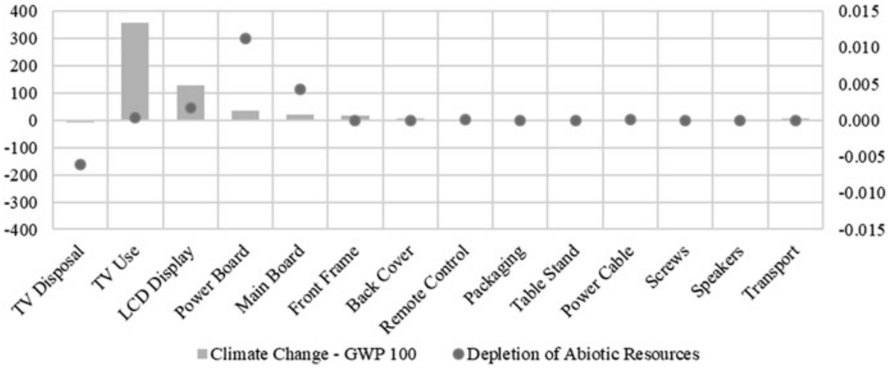

Fig. 5 Comparison between the categories “climate change – GWP 100” and “depletion of abiotic resources – elements and ultimate reserves”

and the power board. In order to produce this component, copper, gold, lead, nickel, silver and zinc are needed. Therefore, the increase in the recycling rate due to the take-back service has a positive impact on the depletion of these materials.

Scenario 2: Premium Warranty Through the configurator the consumer is given the choice to extend the warranty. Assuming a standard use phase of a television with a common two-year warranty, an extension up to 10 years is possible. This scenario includes picking up the damaged television from the consumers home/location and either repairing it or when this is not economically viable, replacing with a new television.

In order to assess the significance of the comparison between the warranties, the common excepted useful life of a TV was noted. A study conducted by the Oeko-Institut e.V. and the University of Bonn on behalf of the German Federal Environmental Agency [38] evaluates the use phase assumed in different LCA studies which were conducted between 2007 and 2011. Here, the usage period varies from 6 to 10 years. According to other data collected by the GfK [39], a German market research institution from 2008 to 2012, the usage period of flat televisions is constantly under 6 years.

For the LCA, a coefficient of approx. −27% is calculated as saving of CO_2 emissions. This number consists of the approach that 63% of the devices that were brought into a repair café can be fixed. However, over time, the unavailability of some spare parts is increasing, up to 36% in the 10th year. Together with the baseline approach of CO_2 emissions per year, a coefficient is calculated, which is also implemented in the environmental LCIA and this scenario. While a standard user who is assumed to change his television after 6 years needs one and two-thirds of a television in 10 years, the “premium” consumer only needs one TV over this time period. During the warranty period, some televisions have to be repaired or replaced by the manufacturer. All in all, in comparison to one standard television set, approx. 27% of the production and disposal phase can be saved. While the assembly and disposal phase are affected by the premium warranty, the use phase

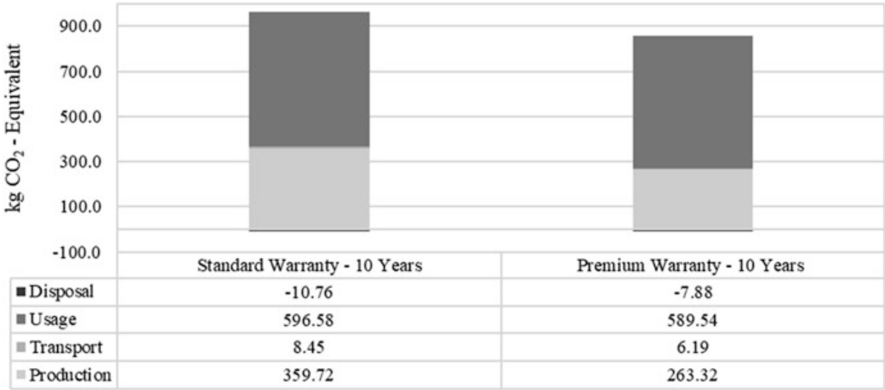

Fig. 6 Scenario 1: Impact of premium warranty. (CML (baseline) climate change – GWP 100)

is enlarged from 6 to 10 years, assuming that the energy efficiency is not increasing with reparations or exchange of the television. Neither it is downgraded by a longer use phase. In case of the second television that is needed when standard warranty is selected, it is assumed to balance its improved efficiency by its possible bigger screen size or developed technology.

In order to analyse the various aspects of the premium warranty, the method CML (baseline) climate change – GWP 100 is analysed in Fig. 6. showing the amount of CO_2-equivalent of the two described scenarios observing a use phase of 10 years, broken down to the impact of the single life cycle phases.

As during this premium warranty period, some television need to be repaired or changed, material is needed. Overall, the savings resulting from production, transport and disposal are approx. 103 kg CO_2-equivalent. In order to illustrate the savings of CO_2 even better, Fig. 7 shows as positive value of the amount of CO_2 that is emitted during a standard warranty usage period over 6 years. The negative value bar illustrates the savings due to premium warranty. This diagram presents the positive impact of the decision for premium warranty model even better in comparison to the standard.

Choosing premium warranty has both a positive impact on the environment and a financial benefit for the consumer. First, approximately 18% of the amount of CO_2-equivalent can be saved in comparison with a standard television set which is used 6 years. Second, two-thirds of the price of the second televisions are saved as well.

Scenario 3: Switch to Renewable Energy Provider In the life cycle of this television set, the use phase is the highest contributor in terms of the global warming potential, as it "produces" the largest amount of CO_2-equivalent. The share in renewable energies in 2014 in Germany was 26.2% [40]; hence, this scenario applies to almost one-third of the energy used to run a television. The calculation of different energy providers and energy mixtures is based on the assumption that the television will be used in Germany. The chosen energy inputs in the use phase for each scenario together with the corresponding parameter are shown in Table 1.

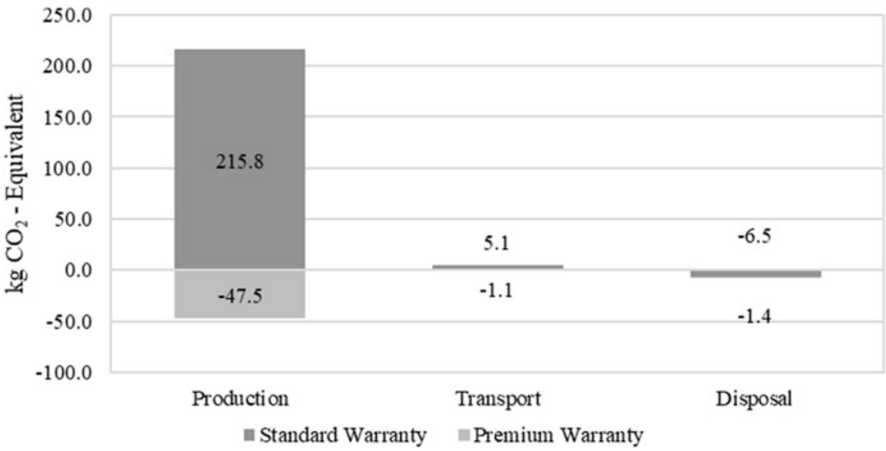

Fig. 7 Savings of premium warranty compared with standard warranty. (CML (baseline) climate change – GWP 100)

Table 1 Definition of the different energy mixes

Scenario	Energy flow (ecoinvent 3.2)
Standard EU mix	Electricity, low voltage | market group for electricity, low voltage – UCTE
German energy mix	Electricity, low voltage | market for electricity, low voltage – DE
Swiss energy mix	Electricity, low voltage | market for electricity, low voltage – CH
Swiss energy mix, label-certified	Electricity, low voltage, label-certified | market for electricity, low voltage, label-certified – CH

The standard scenario is calculated using a European energy mix that shows the interchange between 24 countries in the EU [41]. Datasets for renewable energy were limited, and as such a Swiss renewable dataset was used – which was certified "naturemade" by the Association for Environmentally Sound Energy, Switzerland. The label ensures that the energy is from 100% renewable or even ecological sources [42].

First, the CML (baseline) category "climate change – GWP (100)" was calculated for the modelled scenarios, the results of which are presented in Fig. 8. As the energy mix only influences the use phase of the television, the production, transport and disposal phases were combined into one category.

The results indicate that different energy mixes have a great impact on the global warming potential of a television set. In general, the Swiss energy mix has a small contribution to climate change, and the Swiss label-certified energy's contribution is only 5.8% on the whole life cycle, so the overall amount of CO_2-equivalent that is emitted is 226,51 kg CO_2-equivalent. The German energy (2014) mix consists of around 26.2% of renewable energy [40]. The renewable energies in 2014 themselves mainly consist of on- and off-shore wind energies, photovoltaics, biogas and hydropower [43]. In comparison, the Swiss energy mix in 2014 mainly

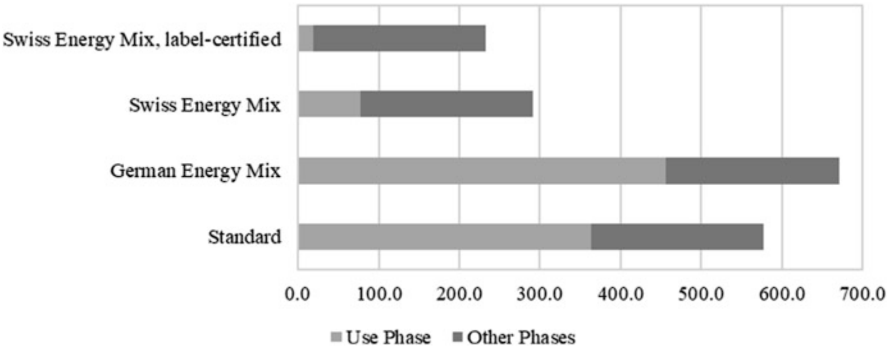

Fig. 8 Global warming potential of different energy mixes during use phase. (CML (baseline) climate change – GWP 100)

consists of renewable energy, which are mainly hydropower energies (64.2%) and nuclear energy (33.5%) [44]. These energy sources are known to be low-carbon. Therefore, the overall lower amount of CO_2-equivalent, which is emitted during the use phase, of the Swiss energy mix compared to the German energy mix is explicable. The selection of the energy provider for the use phase is crucial for the overall carbon footprint of the television. In case of the energy provider, the implementation of a sustainable service can have significant positive impacts on the sustainability of the television.

6 Discussion and Conclusion

6.1 Key Findings and Major Contributions

There exist several environmental assessment methodologies which can vary significantly by their input requirements, complexity, environmental focus and application on business operations. In the initial application of PSS on mass customization, it is advisable that the methods of performance and its interaction with the company's data are developed with experts in the relevant fields of knowledge. At this stage, we consider that an environmental assessment method that also includes a life cycle thinking perspective is imperative when using PSS in MC.

As PSS would require special focus on the life cycle phases of the product for different components and materials, the problematics on gathering external data may be even more significant. For the success of using PSS in MC, close relationships to these experts are advisable. With the help of policy recommendations and the creation of networks for exchange, these barriers can be overcome, and the PSS can be developed more accurately.

While observing the sustainability of PSS, focussing on the whole life cycle is a key aspect to evaluate the environmental impacts. A full-scale life cycle assessment is therefore advisable to validate the outcomes of simplified calculations. Furthermore, the close examination of the life cycle highlighted the main contributor for negative environmental impacts, which in consequence can lead to an evaluation of the meaningfulness of the different PSS. The comparative scenarios showed that the impact of the apparent main contributor "energy" can be easily reduced by a switch in the energy provider. As the general amount of renewable energies is increasing, the focus for sustainability will shift to the production phase. Therefore, the interest particularly in the extension of the use phase and the recycling of the disposed devices is increasing in order to create a sustainable MC television. This challenges the PSS to focus on the end-of-life phase to enhance a closed-loop life cycle. To achieve this, a close relationship between the MC company and the stakeholders associated with the production and disposal of the device is required. The consumer is also an important stakeholder, as they come to the fore in the MC approach, especially, since the level of sustainability depends on their selection of PSS. Thus, when the PSS and their effect on the environment are advertised properly, the services provide a good opportunity to raise the level of sustainability.

6.2 Limitations and Further Research

The barriers of data collection and exchange of data beyond internal business operations may be overcome more easily if businesses within an industry and with support of policy would collaborate and set up data platforms and networks for a better exchange of information.

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Effects of Mass Customization on Sustainability: A Literature-Based Analysis

Paul Christoph Gembarski, Thorsten Schoormann, Daniel Schreiber, Ralf Knackstedt, and Roland Lachmayer

Abstract Sustainability has become increasingly important to business research and practice. Approaches, which support fundamental changes in behavior to act economic, ecological, and social, are required. A popular concept that contributes to these challenges is mass customization (MC). MC—defined as a competitive strategy—allows for producing goods and services for individual needs of customers. In doing so, it, for example, helps toward an increased product-customer relation, efficient production, and a high degree of personalized goods, which may have positive effects on the society and the environment (e.g., by reducing waste). In order to get an overview of which effects of MC toward sustainability are discussed, our study aims to synthesize prior literature. Therefore, we conduct an extensive literature review in different search engines to ensure a broad view on this topic. As a result, 33 articles that met our research purpose are obtained. These articles are coded by three researchers independently and—a total of 157 codes—are consolidated afterward to determine effects of MC on sustainability. Our classification indicates that mostly social (∼87%) and economic issues are addressed (∼84%), while ecological aspects are underrepresented.

Keywords Mass customization · Sustainability · Effects · Literature review

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1 Introduction

The rapid deterioration of the natural environment as well as concerns over wealth disparity and corporate social responsibility present elementary issues for our entire society [1, 2]. In order to contribute to these challenges, sustainability has increasingly gained importance in business research and practice [3–7]. In addition, there is an increased cultural and legal pressure, which also leads to more recognition of sustainability in businesses [2, 8]. Thus, approaches that support fundamental changes in behavior and practice are required. One approach to tackle these challenges is given by innovative business models that include new strategies, for example, business models that allow individualizing products or increasing the quality in order to enable a stronger relationship between customer and product that may reduce the "throwaway society." Here, the concept of mass customization (MC) comes into play.

Defined as competitive strategy in the 1990s, MC targets at tailoring goods and services to individual customer needs at mass production efficiency [9]. Two key tools of MC are (1) customer integration in a codesign process and (2) robust process design, for example, through modularization of product and service constituents [10]. The effects of modular product structures on sustainability and their potentials for circular economy (ecological) are well understood (e.g., [11]). However, whether MC as competitive strategy addresses sustainability holistically is at least questionable.

In this context, the term sustainability is used for two different meanings. First, in the meaning of persisting business relationships, which says that due to the customer interaction and involvement during product specification and codesign, a customer is not willing to change to another supplier because teaching the supplier about individual needs and habits would start from the beginning [12]. Second, sustainability is understood as adapting current activities to the requirements of future generations [1]. In this article, we focus on the second meaning of sustainability.

The addressed topics of MC and sustainability as well as corresponding business models are discussed in different disciplines. Thus, our study aims to achieve the following goal: *synthesize prior literature from different perspectives—information systems, business models, and MC—in order to identify the status quo of sustainability in MC, including social, ecological, and economic aspects*. Based on the current state, we discuss the research gaps identified and further research potential. Our contribution is a literature-based synthesis of effects and principles of sustainability in MC. Therefore, we carry out an extensive literature review that consists of five steps, namely, definition of scope, conceptualization of topic, literature search, literature analysis and synthesis, and research agenda [13]. Accordingly, after specifying the scope of our study—identifying effects of MC on sustainability (Sect. 1)— we conceptualize the topics of sustainability and MC (Sect. 2). Based on the research methodology (Sect. 3), we identified 220 articles and obtained 33 articles that met our research purpose. Next, we apply an inductive approach (e.g., [14]) in which we analyze each of the 33 articles derived to classify different effects and principles of sustainability in MC. As a result, our classification indicates that mostly social (∼87%) and economic issues are addressed (∼84%), while ecological aspects are underrepresented (Sect. 4). Moreover, we critically reflect the results, outline limitations of our study (Sect. 5), and conclude with our main findings (Sect. 6).

2 Related Work

2.1 Sustainability

Sustainability first came up in 1987 from the World Commission of Environment and Development (WCED), which is also known as the *Brundtland report*. They define sustainability as “the development which meets the needs of the present without compromising the ability of future generations to meet their own needs” [1, p. 43].

Dimensions of Sustainability Sustainability is a booming concept and a frequent used, broad term [15]. To handle the complexity of this term, it is usually divided into three dimensions, for example, *triple bottom line* and *three-pillar model* (economic, environmental, and social) and *triple Ps* (people, planet, and profit) [16, 17]. *Economic sustainability* focuses on efficient and responsible use of resources to enable a long-term offering of a certain product or service as well as long-term generation of profit. Corresponding aspects are, for example, performance, finances, market presence, and repurchase rates. *Ecological sustainability* refers to the consumption of resources in a sustainable manner in order to reduce environmental impacts, for example, by reducing energy use, emissions, and waste. *Social sustainability* deals with ensuring well-being of the people involved in an organization, for example, by improving working conditions or contributing to diversity, equality, and health.

Although the *three-pillar model* is very common [17], the analogy of a house is often criticized because of the unequal consideration of such dimensions, for example, if one pillar breaks, it does not have a direct impact on the entire house [18]. Thus, often the representation with a triangle is preferred (Fig. 1), which highlights that the value of each dimensions can be variable and in conflict to each other (e.g., environmental friendly resources may have negative economic effects).

Strategies of Sustainability For implementing sustainability in consumption and production, typically, three strategies (efficiency, consistency, and sufficiency) are distinguished [19, 20]. *Efficiency* aims at achieve resource efficiency. Basically, the purpose is to reduce environmental damage by optimizing input-output rations of production or consumption [21]. Often, it tends to enhance sustainability just a little because there is no elementary change in behavior. *Consistency* focuses

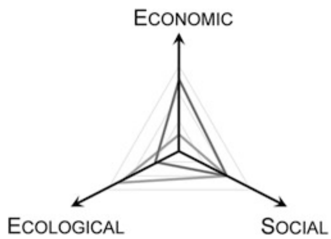

Fig. 1 Triangle of sustainability

at considering circular approaches. The goal of it is to create no waste because every output is reused in further steps. *Sufficiency* aims to achieve fundamental changes of habits, for example, by changing current patterns of consumption and production behavior. To address these issues, new and innovated business models can contribute [21].

However, as this section indicates, in contrast to the meaning of long-life cycles or persisting business relationships, there are various issues that should be considered if sustainability—in the second meaning (Sect. 1)—is meant.

2.2 Sustainability and Mass Customization

Although the concept of MC was introduced as competitive strategy more than 20 years ago [9], research that integrates MC and sustainability is still at the beginning. One of the main hypotheses is that MC, due to addressing individual customer needs, is able to reduce overproduction and resource consumption as well as to extend the product usage phase of the life cycle [5]. The existing research stream can be divided into three directions: (1) the description of impact factors of MC and MC enablers on sustainability (e.g., [22]), (2) the discussion of business models for sustainable MC (e.g., [6]), and (3) the analysis of consumer purchase decisions (e.g., [23]).

Impact Factors of Mass Customization Existing studies usually take a life cycle-oriented approach to identify impact factors or effects of MC and its enablers on sustainability. Pourabdollahian et al. [22, 24] derive impact factors for design, manufacturing, distribution, usage, and the end-of-life phase of mass customized goods. In their deductive analysis, environmental and partly social aspects were focused. On the one hand, the study remains conceptual and does not lead to a definition of measurable key performance indicators. On the other hand, the authors limit their analysis partly to the impacts of modular product structures as an enabler for MC.

Boër et al. [5] concentrate on the stable solution space in design and manufacturing as a MC key principle. In their project "Sustainable Mass Customization – Mass Customization for Sustainability (S-MC-S)," they developed a sustainability assessment model based on measurable economic, environmental, and social indicators. Although the assessment model is very detailed it has a strong focus on the production of mass customized goods. Other life cycle phases or other MC key principles like co-creation are not represented.

In her study of sustainability aspects of distributed production, Kohtala [25] also reviewed literature on MC. She found that single sources discuss the sustainability of MC in comparison to mass production. Other sources derive frameworks and models for sustainable MC, but these have a clear focus to operations management and remain mainly conceptual with only little validation. The majority of sources considered for the review deals with product design touching eco-design, product longevity, and customer involvement not only in codesign but also in coproduction. The result of the study is a landscape where MC is analyzed regarding distributed production, environmental benefits and environmental concerns. Detailed assessment frameworks or models are not implemented or discussed.

Business Models for Sustainable Mass Customization Regarding business model innovation, Osterwalder's Business Model Canvas [26] is widely used to formulate and visualize existing and potential models. Pourabdollahian et al. [27] use this framework to discuss a generic MC business model and the impacts of MC enablers like robust production processes, modular product design, or delivery at point of sale on the indicators *waste production*, *energy consumption*, and *emission*. The results are survey based and rely on data from academia and footwear industry.

Hora et al. [6] use the Business Model Canvas in a different way. In their work, a framework to help companies in formulating sustainable MC business models is synthesized (Fig. 2). Therefore, four key principles of MC (co-creation, modularity, platform, and build to order/postponement) are merged with sustainability enablers.

Consumer Purchase Decisions Single studies address the field of consumer choice research and examine purchase decisions in dependency of product customization and sustainability. As an example, Hankammer et al. [23] explored purchase decisions of consumers in Germany and China revealing that the impact of sustainability on the choice is higher than that of customization.

SMC Framework		
Sustainable Solution Space Development (Co-Creation + Modularity + Eco-Design)	**Produce only what You (can) sell** (Build-to-order + Efficiency)	**Sustainable Usage** (Co-Creation + Eco-Design + Efficiency + Awareness)
Sustainable Configuration (Co-Creation + Platform + Eco-Design + Awareness)		**Product Stewardship** (Platform + Co-Creation + Dematerialization + Circular Economy + Longevity)
Recyclable and Upgradable Products (Modularity + Platform + Longevity + Circular Economy)		**Additional Services** (Platform + Longevity + Dematerialization)

Fig. 2 SMC Business Model Framework. (Source: Hora et al. [6])

Overall, sustainability and customizability are both attractive to consumers. However, no general framework for the sustainability of MC is at hand; existing approaches are limited to either single stages of the product life cycle, single MC enablers, or single facets of sustainability. Business model frameworks for sustainable MC document interdependencies between MC key principles and sustainability enablers, but the effects of MC on sustainability are discussed here only to a minor degree.

3 Methodology

In order to classify, which effects MC has on sustainability, we conducted an extensive literature review. A rigorous literature review requires a proper structure and the disclosure of the entire process including the selection of keywords and sources, the derivation of search phrases, the specification of evaluation criteria, etc. [13, 28, 29]. Due to the methodological rigorousness of reviewing literature, we follow the five steps, which are recommended by [13]: (I) definition of review scope (Sect. 1), (II) conceptualization of topic (Sect. 2), (III) literature search (Sect. 3), (IV) literature analysis and synthesis (Sect. 4), and (V) research agenda (Sect. 5).

Accordingly, we started with the analysis of the topics (sustainability and MC) to identify suitable keywords. Initially, for the identification of adequate search items, we evaluated various items including *mass customization*, *business model*, *mass customization business model*, *sustainability*, *environment*, *ecological*, *social*, and *economic*. In order to determine a useful search string, we combined the search items selected and evaluated the initial articles provided by different sources regarding our research purpose. As a result, we derived a final phrase, which has to be slightly adjusted for each database and search engine used (Table 1).

Next, we selected databases and search engines. First, we choose Google Scholar to get a broad and interdisciplinary overview of prior research including various studies and academic papers. Because of a continuous, decreasing compliance of the articles regarding our research purpose, we only considered the first ten pages of Google Scholar. Second, to include specific MC-specific literature, we selected the proceedings of the Mass Customization & Personalization Conference (MCPC) and the proceedings of the International Conference on Mass Customization and Personalization in Central Europe (MCP-CE). Finally, to get information that deals

Table 1 Final search phrases

Source	Search phrase
Google Scholar	"mass customization" AND ("sustainability" OR "sustainable")
AISeL	("mass customization" OR "mass-customization") AND "business model*" AND (sustainable OR sustainability OR ecologic** OR environment** OR social OR economic**)

* one unspecified letter; * unspecified ending

with MC, business models and required information systems, we selected the Association of Information Systems electrical Library (AISeL), which provides leading journals and proceedings of the information system research field. This focus also reflects the three existing research streams (Sect. 2.2). After analyzing the first results, we excluded literature that focuses on enablers for MC and challenges to carry out MC, which do not provide concrete effects regarding sustainability.

In the next step, we used an iterative approach to classify the papers identified within a concept matrix. In total, we ran through four iterations until all articles from the literature review were classified. For each iteration, we applied an inductive approach (e.g., [14]). First, we coded articles relevant from Google Scholar (iteration 1). Second, we included articles that are provided by AISeL (iteration 2) and, third, MC-specific literature (iteration 3) to revise our classification. In each of the iterations, all relevant articles were coded and classified by at least one researcher independently. Finally, we consolidated the results in a follow-up workshop as well as determined codes (here, effects) and categories with all three researchers (iteration 4).

4 Literature Analysis and Synthesis

4.1 Classification of Results

In total, we found 220 articles. As proposed by [29], a complete keyword search as well as an evaluation of titles and abstracts was applied to each article (Evaluation I). Nonrelevant articles were eliminated. The remaining articles ($n = 76$) were verified by the full text (Evaluation II). Finally, we removed duplicates (consolidation). In total, we found 33 relevant articles (Fig. 3). In order to contribute to the reliability and validity, the relevance of each article was evaluated by at least two researchers.

In order to get an initial overview of the articles identified (Table 2), we listed them, marked them with an *ID* (consecutive number), a *reference* (article authors), and to a dimension of *sustainability* (economic, ecological, and social). According to Table 2, the included literature focusses on social or economic sustainability.

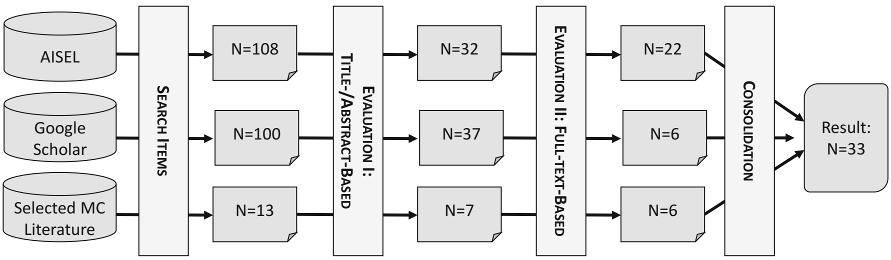

Fig. 3 Overview of search process

Table 2 Overview of relevant articles

[ID]	References	Sustainability		
		Economic	Ecological	Social
01	Bazijanec et al. [30]	•	•	•
02	Heikkilä et al. [31]	•	–	–
03	Böhm et al. [32]	•	–	•
04	Reichwald et al. [33]	•	–	•
05	Moeslein and Piller [34]	•	•	•
06	Piller et al. [35]	•	•	•
07	Gerards et al. [36]	•	–	•
08	Nath et al. [37]	•	–	–
09	Chowdhury et al. [38]	•	•	–
10	Kruse [39]	•	–	•
11	Ives and Piccoli [40]	•	–	•
12	Habryn et al. [41]	–	–	•
13	Kruse [42]	•	–	•
14	Hildebrand et al. [43]	•	–	•
15	Beverungen et al. [44]	•	–	•
16	Fichman et al. [45]	–	–	•
17	Zainuddin and Gonzalez [46]	•	–	•
18	Thiesse et al. [47]	•	–	•
19	Akkinen [48]	–	–	•
20	Schlagwein and Bjorn-Andersen [49]	•	–	•
21	Lee et al. [50]	–	–	•
22	Eiletz-Kaube and Ksela [51]	–	–	•
23	Niinimäkia and Hassib [52]	•	•	•
24	Shrouf et al. [53]	•	•	–
25	Hansen et al. [54]	•	–	•
26	Gandhi et al. [55]	•	–	•
27	Gembarski and Lachmayer [56]	•	–	•
28	Hora et al. [6]	•	•	•
29	Hankammer et al. [23]	•	–	•
30	Pourabdollahian et al. [22]	•	•	•
31	Pourabdollahian et al. [27]	•	•	•
32	Boër et al. [5]	•	•	•
33	Pourabdollahian et al. [24]	•	•	•

Approximately 87% of the analyzed papers address economical and also 87% address social sustainability. With the aspect of environmental sustainability, only 11 out of 33 papers are concerned, which is equivalent to 33%. Over 78% of the paper deals with at least two aspects, almost 25% even with all three of them. As a result, almost 22% focus exclusively on one aspect, but none of the publications found are related exclusively to the aspect of ecological sustainability.

4.2 Synthesis of Effects

Next, we classified the articles obtained by using a concept matrix (Table 3), which is divided into three dimensions: *category/effect of MC* (coded from each article), *sustainability* (economic, ecological, and social), and *appearance in reference* (source of the codes). Each of the 24 codes can be described by one or more characteristics.

As Table 3 highlights, 24 different effects of MC were coded during the analysis. One hundred fifty-seven items were detected (including multiple mentions), with 16% (25 items) being attributable to the "individualization (customer needs)" effect. This is by far the most frequently mentioned, more frequent notifications being "efficient production" (8.3%), "increased customer satisfaction," "mass confusion (customer)," "easier access to information (producer)," "cost reduction," as well as "increased product complexity (producer)" (all 5.1%). The other effects are in the adjoining area up to just one mentioning. Compared to Table 2, the small consideration of the aspect of ecological sustainability is even more explicit. Only three effects can be attributed to this aspect. In the pure consideration of the links of the effects to the aspects of sustainability, 3 effects are related to the ecological sustainability (12.5%), 17 effects to the economic sustainability (70.8%), and 10 to the social sustainability (41.7%). If the frequency of the mentioning is also taken into account, i.e., a weighting is carried out accordingly, the general tendency still persists. The aspect of ecological sustainability is getting even less discussed since it is only indicated by ten of the entries (6.4%).

5 Discussion and Further Research

5.1 Discussion

This contribution addresses a holistic perspective on effects of MC related to sustainability. Although we did not focus on single MC enablers, their impacts are mirrored in the evaluation to a certain degree. As an example, modular product architectures hide behind the codes "production-product complexity," "cost-efficient production," "costs-cost reduction," and to a certain degree in "CRM-individualization." Furthermore, the analysis indicates that indeed all three dimensions of sustainability are discussed in line with MC but the ecological one only to a minor degree. Nevertheless, this result has to be seen in a differentiated context: (1) when the analysis shifts from a holistic point of view to the single MC enablers and in particular to modular architectures and product platforms or (2) when the focus is set to a single phase of the product life cycle, in particular to production, single considerations of sustainability assessment models and discussions of the effect on environmental degradations appear. In reverse, this confirms statements of single authors that assess publications on impact factors and effects on MC on sustainability as mainly conceptual.

Table 3 Resulting concept matrix

Category/effect of MC		Sustainability			Appearance in reference [ID]
		Economic	Ecological	Social	
Finances	Increased profits	•	–	–	[1, 7, 28, 29, 32]
	Reduced costs	•	–	–	[1, 5, 9, 17, 28, 30, 32]
	Increased competitive advantages	•	–	–	[1, 4, 27, 32]
	Efficient production	•	–	–	[4–6, 8, 15, 17, 18, 26–28, 30–32]
	Reduced safety stock	•	•	–	[5, 32]
	Reduced information costs	•	–	–	[5, 27]
	Increased willingness to pay	•	–	•	[5, 6, 14, 27–29]
	Efficient marketing	•	–		[5, 27, 28]
	Successful business model	•	–	–	[3]
Customer relation	Increased individualization and personalization (addressing customer needs)	–	–	•	[1, 3–7, 10–18, 22, 23, 25–33]
	Stronger customer relationship	•	–	•	[4, 20, 24, 26, 27, 30, 31]
	Fear to claim (customer)	–	–	•	[6]
	Group-based individualization	–	–	•	[6, 25, 27]
	Increased trust	–	–	•	[19]
	Increased customer satisfaction	–	–	•	[5, 7, 14, 21, 27, 28, 29, 31]
	Increased product-customer relationship	•	•	•	[23, 27, 28, 30, 32]

Table 3 (continued)

Category/effect of MC		Sustainability			Appearance in reference [ID]
		Economic	Ecological	Social	
Information and knowledge	Mass confusion (customer)	–	–	•	[1, 4–7, 11, 27, 31]
	Insufficient knowledge to design products (customer)	•	–	•	[4, 6, 7, 27]
	Enabling short-term changes	•	–	–	[5, 11]
	Easier access to information (producer)	•	–	–	[5, 10, 13, 25–27, 31, 32]
Product and production	Short delivery time	•	–	–	[1, 9, 26, 28, 30–32]
	Increased product quality	•	–	–	[9, 26, 29, 32]
	Increased product complexity (producer)	•	–	–	[2, 4, 26, 27, 28, 30–32]
	Waste reduction	–	•	–	[30–32]
	Coverage (count)	18	3	13	

The second interesting point is that eight of the 33 articles discuss the effects of mass confusion and four contributions refer to insufficient knowledge of the customer while configuring his or her individual product. Additionally, eight of the 33 contributions address the companies' ability to access customer knowledge through adequate information systems. This mirrors the importance of product configuration and customer knowledge management systems as success factors of MC.

Another finding of the analysis is that apparently there exists only a little number of differentiated sociological studies regarding the effects of mass customized goods and sustainability on purchase decisions, which is then limited to a certain branch or product. However, this result has to be questioned due to limitations of key words and search engines, which will be briefly discussed in the next subsection. As an example, works from Franke et al. [57] on the "I designed it myself" effect were not included in the search results, although it targets on two of three dimensions of sustainability, namely, social and economic aspects.

Although we found some helpful insights regarding the status quo of sustainability and MC, this study is not free of limitations. The literature review is based on methodological recommendations by vom Brocke et al. [13]. We choose this methodology because it is—in our opinion—appropriate for conducting traceable and expandable literature reviews. However, the selection of keywords and literature sources as well as the classification is conducted by own decisions and choices, which have limitations. First, we could have added more keywords (e.g., "environmental effects"). Second, we could have added more sources (e.g., ScienceDirect, Scopus, or EBSCO)—however, our selection allows for a multidisciplinary overview that includes different perspectives for MC, sustainability, and business models/information systems. An extended search with additional keywords and sources may enable the identification of more literature that contributes to this field (e.g., [58, 59]). Third, a different methodological approach could be applied, for example, expert interviews and surveys.

5.2 Further Research

Future research can be aligned at two points of contact. First, the concept matrix (Sect. 4) directly indicates that some effects, which can be found in literature, could be discussed in a broader sense. This is especially true for ecological and single social aspects like the *fear to claim*, which means that a customer is reserved against claiming for a product that he has partly designed. On the other hand, the evaluation of *safety stocks* in a MC supply network in dependency of flexibility and the ability to allow short-term changes before distribution could integrate a field of research for operations management in the sustainability considerations. As another point here, *group-based individualization* might be an answer to integrate sets of options to a platform and thus raise the efficiency and predictability in production. First approaches can be traced in automotive development.

The second stream for future activities evolves of the three strategies of sustainability. As stated in Sect. 2.1, efficiency, consistency, and sufficiency are major strategies for the implementation of sustainability in a business model. While the efficiency strategy—which contributes only a little—is indeed targeted by MC (e.g., by allowing codesign and by using modular product architectures that lead to efficient production), a lack of consistency and sufficiency can be seen.

Regarding consistency, literature mentions circular economies as an option—however, it is not mapped on MC business models so far. As a result, beside some conceptual considerations, no implementation or documented use case is found in the literature review. In this context, MC has some challenging aspects since an individually configured product is an answer to one specific set of customer requirements that may be completely unique. In that case, recycling is equal to dismantling. But looking on the single product constituents, modular product structures allow reconfiguring and updating a product in order to adapt to changed requirements or to the requirements of a new customer. This perspective leads over to the sufficiency strategy that means changing consumption behavior. Here, the delimitations of two competitive strategies, MC on the one side and supplier of product-service systems (PSS) on the other side, vanish. The resulting business models then lead to completely changed requirements as can be seen in automotive engineering and, for example, car sharing [60]. Adapting the principles of MC to the field of PSS development thus seems highly promising.

6 Conclusion

Considering both sustainability and MC (e.g., in form of innovative business models) is highly relevant for firms. With our literature-based analysis, we addressed a holistic viewpoint regarding the effects of MC on sustainability. Based on a qualitative coding procedure, we determined 157 codes and synthesized them into 24 different effects of MC—in four categories, namely, finances, customer relation, information and knowledge, and product and production. Our contribution, a synthesis of effects, can be used by researchers interested in MC, sustainability, and business models, for example, to position their research (e.g., which category of effects is addressed?) as well as to derive new research questions (e.g., how to contribute to ecological aspects? What effects can be addressed by “I designed it myself”?).

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Exploring Drivers and Barriers for Sustainable Use of Resources: The Case of High-Tech Mass Customizers in the German Textile Industry

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Abstract An efficient and sustainable use of resources is a core task for every company to ensure competitiveness and long-term success. Compared to large companies and corporations, SMEs have fewer capacities and knowledge of how to implement resource efficiency. Therefore, we explored the drivers and barriers for SMEs in order to both overcome existing challenges and address sustainability opportunities. The empirical field is the textile industry in Germany, which is considered particularly interesting due to high competitive pressure, long value chains, and its niche specialization. For this purpose, we conducted 14 interviews with company representatives of textile SME mass customizers in Germany. The results show that there is a wide range of possibilities for a more sustainable use of resources, which help textile companies gain a great economic advantage. Findings include three drivers and barriers each, for SMEs to implement sustainability-focused activities. Managerial implications present both recommendations for the textile industry as well as related SMEs in other domains.

Keywords Sustainable development · Sustainability · Mass customization · B2B · Textile industry

1 Introduction

As our planet suffers from rising overpopulation, a depletion of natural resources and increasing environmental pollution, the need for sustainable development has become an urgent global matter. A company's attractiveness for consumers depends to some extent on how it manages its social responsibility toward global development. The textile industry has an important role to play in sustainable development since it is one of the biggest industrial causes of environmental pollution [1, 2]. In

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Germany, the textile industry has had to undergo many transitions in recent decades in order to meet technological and economic changes. Nowadays, the innovative sector of technical textiles drives growth in Germany and accounts for almost 50 percent of the global market share [3]. However, Germany's current lead role in this sector is increasingly shaken by the influence of other countries, especially by China. The Chinese industry is evolving rapidly from lower price segments to technologically mature solutions and has increased its focus on innovations [4]. This development adds to the pricing pressure for German companies. A seemingly reasonable solution for German textile companies is to outsource production, but several companies have successfully maintained Germany as a production location. Only textile manufacturers positioned in the high-quality segment have grown to the global competition.

In addition to struggling for maintaining a lead role on the global market, German textile companies are facing strategic uncertainties due to dwindling resources [5]. Thus securing the long-term supply of resources becomes a central task for every textile company. Several researchers have pinpointed mass customization (MC) as a business approach that entails a high level of potential for sustainable manufacturing [e.g., 6–8]. The need for a more sustainable use of resources exists in small- and medium-sized enterprises (SMEs) in particular, since they constitute the majority of enterprises [9] but are often less concerned with the issue. Compared to large companies and corporations, SMEs are more limited in terms of time and monetary resources and therefore have less scope for sustainable development. For that reason, they are at the center of interest of this study. Research so far lacks examining the extent of sustainable use of resources in small B2B companies that are narrow specialized. To address this gap, we conducted interviews with company representatives of textile SME mass customizers in Germany to examine how they deal with sustainability issues and to explore its drivers and barriers, which are of many different natures. Environmental, economic, technological, and other factors can all work to either drive or hinder sustainable development. While each driver indicates a step toward more sustainability, each barrier represents an important characteristic of the textile industry that can, if not managed appropriately, reduce or derail the value of sustainable efforts. In the MC context, we define a driver as a factor that motivates a company to realign their MC strategy by tapping the full potential it entails for sustainable development. A barrier, by contrast, we term as a factor that hinders a company from combining their MC focus with the implementation of a more sustainable use of resources.

We identified three main drivers and barriers, respectively, regarding also MC principles such as customer integration and superior value through customization [10]. Accordingly, the companies' customer focus is especially noteworthy and their choice to locate manufacturing in Germany ("Made in Germany") that contribute to sustainability-focused activities, whereas the necessity for textile samples and the challenge of not always knowing the final application represent barriers for B2B marketers. Findings contribute to a deeper understanding of how SMEs of this exemplary branch deal with sustainability-related matters. Moreover, the results serve as a starting point for studies focusing on both overcoming barriers and addressing opportunities. We conclude by deriving managerial implications, also taking peculiarities of the textile industry into consideration, and opening up to related industries.

2 Theoretical Underpinnings

The concept of sustainable development as a guiding principle is based on the 1987 report of the Brundtland Commission: In *Our Common Future*, the 38th General Assembly of the United Nations formulated a global program of change and defined sustainability as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [11]. The concept of sustainability is highly complex since it encompasses many different aspects. The three classical dimensions of sustainability are defined as "triple bottom line": environmental, economic, and social issues [11]. Even though politicians as well as business leaders have done extensive work in the last century on all challenges facing humanity – albeit environmental, economic, or social matters – it was only fully understood at the 1992 Earth Summit in Rio that none of the three problems could be solved without also tackling the other two [12]. The recognition of strong interdependencies of these issues has entailed the efforts for a fundamental change in thinking and in practice of environmental management [13]. Efforts to promote a sustainability transition are reflected by the increase of research on sustainability science [14, 15]. The UN report's definition of sustainability is used by most academic scholars; however, they disagree regarding the meaning of this concept and regarding the direction future sustainability research should take [16].

However, there is a general consensus among researchers that companies can create competitive advantage by focusing their activities around sustainable concepts [e.g., 17–20]. A large number of managers have reached the point of accepting that corporate sustainability is a precondition for doing business [21]. Resource efficiency gives companies a competitive edge by reducing their operating costs, having a positive environmental impact, and contributing to corporate social responsibility [20]. While the positive impact of sustainability on a company's position on the market is well documented theoretically, current literature does not provide insights into ways of implementing these sustainable concepts [19].

Recent research suggests that the textile industry is long due for putting more effort into sustainable development [22, 23]. Production processes for products of industrial textile companies strongly harm the environment – this urges for a more preservative and efficient use of natural resources. The trend toward more environmental protection as well as the globally increasing need for infrastructure is pushing the demand for the highly innovative product group of technical textiles. As a key growth driver in the industry, this product group accounts for more than 50 percent of the textiles produced in Germany [24].

Several studies have examined the development toward more sustainability that has been evident for some time in companies of the apparel industry, which are recognizing the competitive advantage of "green textiles" [24, 25]. In the light of the debate on sustainability, one focus of recent research has been on the analysis of MC concepts with regard to sustainable manufacturing. For example, Hankammer and Steiner (2015) investigate the impact factors of MC on sustainability from a business model perspective [26]. Chin and Smithwick (2009) compare the patterns of MC to those of mass production by breaking down the different stages of the product life cycle [8], and Pourabdollahian et al. (2014) establish a research agenda to identify the role of MC for sustainability [6]. Kohtala (2015) provides an in-depth literature review on all relevant studies covering this subject [7]. These studies have shed light on a multitude of factors that influence a company's sustainability activities. For instance, literature sees MC as a mean to save resources and avoid overproduction [8], suggests a greater customer orientation to achieve sustainable relationships [7], and promotes product longevity [25], closed material loops [6], and local production [27] to increase sustainable use of resources.

However, recent research has not investigated the role that B2B manufacturers of technical textiles play for a sustainable use of resources in the industry. We built upon this gap by examining the following research question: *What are drivers and barriers for sustainable development of SME mass customizers of the German B2B technical textile industry?*

3 Research Design

3.1 Field Setting

This study was conducted within a research project in the textile industry in Germany. This high-tech branch provides textiles for specific applications such as heat and acoustic insulation. All companies have the following three commonalities. Firstly, they are mass-customizing SMEs. Most of them have less than 100 employees and are in a highly competitive environment. Financial and personnel resources are very limited. Secondly, they are narrow specialized in their field and thus rather serve niches. Thirdly, companies are in B2B markets and provide offerings to industrial customers.

In this context, 43 interviews with a least duration of 1 h were conducted with mainly CEOs and also managers of technical textile manufacturers. The interviews covered three main topics, namely, strategy and business model, sales process, and mass customization. Among these interviews, many covered sustainability as one of the main opportunities for future existence of German textile companies. Following Patton's (2002) method, the most constructive interviews were selected with purposeful sampling [28]. All 43 interviews provided information on relevant topics, but only some fulfilled the criteria to contribute to our research. These selection criteria provided that the respondent (A) discussed the topic of sustainable development in general, (B) described concrete barriers or drivers of sustainable resource use in his business environment, and (C) expressed wishes or ideas for improvement of sustainable development in textile companies. In the end, a sample of 14 interviews was selected, which were analyzed in depth in order to get to the bottom of sustainability in the German textile industry.

For data collection, a semi-structured interview approach following Yin (2014) was used [29, p. 69]. Thus, we flexibly adapted the guideline throughout data collection. Topics were derived from the literature. This guideline was improved throughout the process based on the constant comparative method by Glaser (1965) [30].

3.2 Data Analysis

We used the coding procedure suggested by Corbin and Strauss (2008) to ground our qualitative data analysis [31]. The literature described above as well as the interview guideline served to formulate initial codes, looking especially for drivers and barriers for the sustainable use of resources. This code list was then expanded and more focused [30, 32]. The second step condensed the essence of the data and aimed at deepening the understanding of identified drivers and barriers. This approach helps mirroring constructs drawn from the literature (deductively) and exploring new constructs based on the data (inductively). Three researchers analyzed the data in parallel, ensuring that each process informs the other. This approach is in line with recommended qualitative data analysis practice [33]. In order to present the findings, the structure of Gioia, Corley, and Hamilton (2013) was used [34]. First-order concepts are as close as possible to interviewees' statements, while second-order themes present first interpretations and according categories. Aggregate dimensions are, in line with this paper's title, drivers, and barriers.

4 Findings

Following Gioia's systematic resolution of raw data into theoretical interpretations [34], our findings can be depicted in two different dimensions for textile SMEs: *drivers* and *barriers*. We focused our analysis mainly on environmental and economic matters of sustainability, while social factors were not examined in depth. Three main drivers and barriers for sustainable use of resources can be derived from our findings, namely, *Made in Germany*, *product quality*, and *customer focus* (drivers), as well as *textile samples and unspecified final application*, *fast pace of the industry*, and *complexity of the supply chain* (barriers). To substantiate our finding, we display the data structure in Fig. 1. Furthermore, we list selected interview quotes in the appendix to support our data interpretation. All drivers and barriers are presented in depth below.

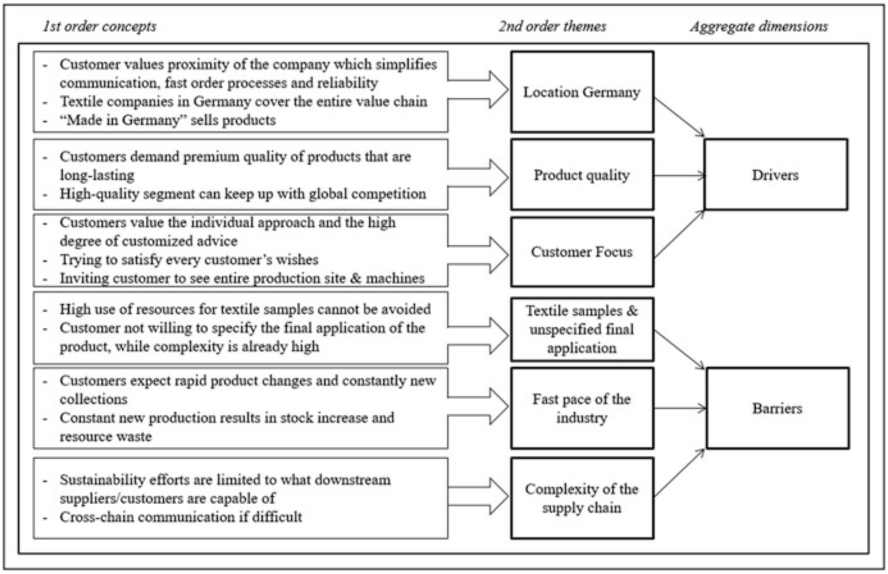

Fig. 1 Data structure of drivers and barriers

4.1 Drivers

Location Germany ("Made in Germany")

The choice to locate nearly all of their production in Germany, which most of the companies have done, reflects their efforts toward sustainable development. The main benefits for locating production in Germany are high levels of innovation, proximity of manufacturers to customers, and a substantial supply of skilled workers (e.g., engineers and managers). In order to meet the challenge of German textile production with an increase in global competition, most companies chose to move into the area of high-quality, functional textiles. It comes as a clear advantage that companies in Eastern Germany still cover the entire textile value chain. Customer needs can be met entirely in Germany. Most companies state the label "Made in Germany" as a clear sales support:

> This is always an argument for sale, of course: Made in Germany. Still, even today. And it is very much appreciated.

The reasons for this are manifold. In addition to the product quality and the possibility to individualize, which the label "Made in Germany" often entails, fast-order processing, trust, and reliability were mentioned as the main factors. Additional opportunities for the German textile industry arise from the increasing demand for synergies between sectors, e.g., between the medical and textile industry. The need for novel products, such as health-sympathetic technical textiles, will grow along with increasing demands of healthcare.

Product Quality

Closely linked to the first driver is the product quality that the label "Made in Germany" often entails. Without exception, each of the examined companies indicated that the quality of their products is very important and in many cases the determining factor for their customers' purchasing decision. The products offer a long product life, which counteracts the enormous acceleration of the downtimes of past years.

In the interests of sustainability, many German textile companies produce on demand only and have to prepare their customers for long waiting periods, since technical product features and complex processes do not permit fast production:

> And we want our customers to understand: sometimes you have to wait for high-quality products. Especially nowadays, with all the possibilities of internet shopping, people expect overnight shipping, the drone might even fly in within an hour. We want to counter these expectations a bit, even if it is contrary to the trend. We're doing well at the moment, we say it's "Made in Germany", we have nothing in stock, it's made to order.

Customer Focus

In order to develop the best solution for the customer, a high level of customer focus and integration is required. Companies do their best to meet the needs of the customers in order to satisfy their wishes, in line with the MC principles of customer integration and creating superior value through customization [10]:

> No sales without content. If you do not make content, if you do not pick up your customers because you do not know your customers - and that's the point - then you will not sell. (...) The question is, can you create a world where someone feels at home, where he feels picked up. And then he buys something.

Another interviewee stated:

> The important thing is to involve the customer in the product, it is our advantage that we do not say "you are limited". Not everything can be done, but mostly everything – and it is important to respond to the customer's request and if it can't be done, we offer him an alternative. Nothing is impossible. Somehow, everything can be solved.

The production in the German textile industry is characterized by a high degree of customization. This gives them an advantage over many of their competitors, which do not offer customer-specific developments and thus cannot react flexibly to the market. As customers greatly appreciate the possibility of individualizing products, the trend among textile companies in Germany toward individualization continues to grow. Productivity might suffer due to huge efforts that companies have by customizing products. In order to improve productivity, several companies pursue mass customization.

4.2 Barriers

Textile Samples and Unspecified Final Application
A high level of resources is used for the creation of textile samples in product development. The process of sampling requires a great deal of personnel, material, and financial resources and can take a long time due to multiple iteration loops. This can be blamed on the fact that the final application is often unknown to the producing company: Some customers retain information that would have been necessary for creating the sample. In order to provide the customer with a solution that meets his expectations, multiple additional loops in the development process are required. Despite the high expenditure of resources, the production of textile samples is inevitable for technical textiles because customer requirements can be highly novel and complex. Therefore, certain technologies for production have to be tested and optimized. In addition, creating samples can be helpful to avoid later inconsistencies with the customer and increase the company's hit rate.

> The more difficult or complicated a market becomes, the worse your business goes, the more samples are produced. Companies try to open up the market somehow based on the motto "The more, the better"....

Furthermore, a textile's haptics plays an important role in this industry: in order to really perceive color, design, consistency, and physical composition of a fabric, the textile has to be touched and felt by the buyer.

Fast Pace of the Industry
Another major challenge for German textile SMEs is the fast-paced development of the industry. Due to the fact that fabrics are subject to fashion, a rapid product change is expected in many areas of the textile industry. Acceleration of the collection cycles can lead to an increase in inventories and a large amount of resources remaining or being wasted:

> We still have the [warehouse] in the house, which is a matter of huge expense here, and we have to sell everything in a certain time period, because we have only limited storage capacity. You have to say, okay, after four years, a product runs out of fashion. I still have those products in stock though, that have to be sold. So who still buys it? What do I get for it? It's a matter of huge expense and unused resources.

In addition, the optimum utilization of the machines might not be possible due to a lack of financial or human resources. On top of that, the conversion of machines is very time-consuming as well as personnel-intensive.

Complexity of the Supply Chain
The complexity of the textile chain is in many respects a challenge for textile manufacturers. A company's activities must be aligned to the entire textile chain, that is, to the competences of downstream suppliers or customers. Sustainable efforts reach their limit:

> On the one hand, the textile industry is enormously modern in terms of logistics, almost everything is just-in-time, but on the other hand it is very difficult to change the entire production chain.

If a link in the chain is weakened, the downstream process stages are affected as well and restricted in their flexibility. Therefore, economic stability should be taken into account when choosing a supplier, as failures and weaknesses can also have a major impact on the supplier. Added to this is the difficulty of cross-chain communication:

> This is the main problem of the textile chain. They only communicate to the next chain link. But the next chain link only wants to buy a product. In today's world, the key is to sell a solution. The end-user needs the solution. If he has no solution, because he has no need, he does not need your product. And if your product-solution-communication gets stuck at any point, you cannot sell it.

5 Discussion and Conclusion

In this paper we explored the status quo of current sustainability levels in German textile B2B companies and analyzed the drivers and barriers for SMEs to overcome existing challenges and to implement sustainable processes. Three drivers and barriers are derived, namely, *Made in Germany*, *product quality*, and *customer focus* (drivers), as well as *textile samples and unspecified final application*, *fast pace of the industry*, and *complexity of the supply chain* (barriers).

This paper contributes to the emerging body of sustainability by shedding light on the challenges and potentials textile companies have in using resources in a more conscious and sustainable manner. Our results conform to findings of previous studies on MC and sustainability and further advance research in this field of study, analyzing a niche of the textile industry that previously has not been examined thoroughly. The focus of our analysis lies on SMEs, which are particularly interesting regarding this topic because they have fewer capacities than large companies while p. ex. underlying the same regulations. Our findings serve to better understand how SMEs can contribute to global developments. It also informs other research streams as follows. First, hybrid value creation [35] or product service systems [36] can influence sustainability of SMEs. Increasingly complex products and growing requirements of B2B customers can be addressed by combining products and services – and along the way contributing to environmental protection and sustainable use of a company's resources [37]. As a result of increased service offers, it is not only the economic but also the environmental dimension of sustainability that is taken into account. With this strategy, a company considers the entire life cycle of the offered product and can positively influence it. Innovations in the technical design of the product parts can extend the service life of a product. This results in the highest possible product utilization, which represents an opportunity for companies and the environment. Another conclusion that the results at hand lead to is that the challenges of the textile value chain must primarily be countered by intensified networking and cooperation between the companies. Through long-term and trusting partnerships, the advantage the German textile industry has due to its closed supply chain can be optimally utilized.

Further managerial implications include the implementation of certification systems that help companies label their sustainable performance. One of the most important environmental management standards worldwide is DIN EN ISO 14001; sustainable resource use in the textile sector is often certified by Oeko-Tex; several other certifications exist. However, certifications are not mandatory and still quite costly, which is why many companies do not invest in complying with the requirements for a certification. Globally uniform standards would be useful to harmonize the conditions of competition for all companies. This would also reward the efforts of the companies already investing in sustainability, which currently still have a cost disadvantage. Additional implications address the potential to increase a company's resource efficiency, which include the reduction of costs for material, the utilization of environmentally friendly energy sources, and promotion of recycling, among others.

Limitations of our study are in the areas of qualitative research, since we only have a small sample. Quantitative studies may be based on our research. Moreover, we were limited to the textile industry. However, this industry exhibits characteristics that are similar to others, such as a fast-paced development or an increasing demand for products with higher quality. Although measures for conscious use of resources are important building blocks, they may not be sufficient for a sustainable development. The vision is to implement sustainability at the core of every company as the fundamental foundation of its business. For this purpose, long-term structural changes are necessary, which could not be referred to in this paper. Moreover, the present study confines itself to the textile industry in Germany – a study comparing the sustainability of the textile industry in Germany with other states or regions would be another starting point for valuable results.

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Appendix I: Data Supporting Interpretations of Second-Order Themes

Dimension	Themes	Representative quotes
Driver	Made in Germany	"This is always an argument for sale, of course: Made in Germany. Still, even today. And it is very much appreciated."
Driver	Product quality	"And we want our customers to understand: Sometimes you have to wait for high-quality products. Especially nowadays, with all the possibilities of internet shopping, people expect overnight shipping, the drone might even fly in within an hour. We want to counter a bit, even if it is contrary to the trend. We're doing well at the moment, we say it's made in Germany, we have nothing in stock, it's made to order."
Driver	Customer focus	"No sales without content. If you do not make content, if you do not pick up your customers because you do not know your customers - and that's the point - then you will not sell. (...) the question is, can you create a world where someone feels at home, where he feels picked up. And then he buys something." "The important thing is to involve the customer in the product, it is our advantage that we do not say 'you are limited'. Not everything can be done, but mostly everything – And it is important to respond to the customer's request and if it can't be done, we offer him an alternative. Nothing is impossible. Somehow, everything can be solved."
Barrier	Textile samples and unspecified final application	"The more difficult or complicated a market becomes, the worse your business goes, the more samples are produced. Companies try to open up the market somehow based on the motto 'the more, the better' . . . "
Barrier	Fast pace of the industry	"We still have the [warehouse] in the house, which is a matter of huge expense here, where we have to sell everything again in a certain time, because we have only limited storage capacity. You have to say, okay, after four years, a product runs out of fashion. I still have those products in stock though, that have to be sold. So who still buys it? What do I get for it? It's a matter of huge expense, these unused resources."
Barrier	Complexity of the supply chain	"On the one hand, the textile industry is enormously modern in terms of logistics, almost everything is just-in-time, but on the other hand it is very difficult to change the entire production chain." "This is the main problem of the textile chain. They only communicate to the next chain link. But this link only wants to buy a product. In today's world, the key is to sell a solution. If he has no solution, because he has no need, he does not need your product. And if your product-solution-communication gets stuck at any point, you cannot sell it."

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A Preparatory Approach to Environmental Assessment for Sustainable Mass Customization

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Abstract Mass customization (MC) is a growing trend in industry that fulfils the demand of customers for personalized products and services. Parallel to customization, more regulations and demand for sustainable products and environmental business practices have increased importance on the agenda of businesses today. However, the knowledge about the implementation of sustainable mass customization (SMC) models is still mainly theoretical. The SMC Excel project presents an approach for the development of an SMC environmental assessment based on life cycle assessment (LCA) methodology for a TV. The environmental assessment method denominated SMC Excel Sustainability Approach (SESA) presented in this study aims to provide reliable information of the environmental impacts of a product (TV) while serving as an efficient and applicable assessment methodology for MC. General requirements for the SESA are described and applied to a case study of a TV. Furthermore, the result of a full-scale LCA of a standard TV model is compared with those impacts obtained by SESA, which indicated that the variance between both results is nominal and, thus, SESA can represent a valid approach for environmental assessment methodologies. Additionally, with the test case scenario of a take-back service where both methods are compared, the impact disparity is similarly low. Nevertheless, further research and testing are required in order to improve accuracy and methodological procedures of the SESA method.

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Keywords Environmental assessment method · Life cycle assessment · Mass customization · Sustainability

1 Introduction

Today's businesses are faced with a growing demand from customers for more personalized products and services. Many companies have already incorporated mass customization (MC) either as an extension or as the main foundation of their business model [1]. MC, however, brings many challenges for the traditional mass production processes as well as the logistics and communication channels [2, 3]. Additionally, with the increasing demand from policymakers and customers for more sustainable business practices and products, MC business models have to include efficient structures not only at the business process level but also at the sustainability performance level.

In present industrial practices, sustainability performance is measured through indicators or assessment methods that are selected according to different criteria such as the sustainability focus (e.g. environment, health) or business type (e.g. chemical products) [4]. The best-known environmental assessment methodology is life cycle assessment (LCA), which is defined in ISO 14040 as the "compilation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle" [5]. However, LCA application can present several barriers for businesses due to its high complexity, demand for high-quality data and considerable requirements in terms of monetary and human resources [4]. According to a survey from the Finnish Environment Institute in 2010, LCA is mostly being adopted in companies that have developed customized and streamlined methods based on LCA [4]. Also in the framework of sustainable mass customization (SMC) business models, developing a new, adaptive environmental assessment method is essential to ensure the integration of environmental parameters on business processes and decisions, especially when these business processes are contrasting to the business-as-usual models that we know. The following sections describe the analysis of requirements and guidelines based on the results obtained from the SMC Excel project in order to contribute to future developments of an effective environmental assessment method for SMC business models.

2 Background

2.1 Environmental Assessment Methods

Numerous methodologies/indexes deal with sustainability measurements, which are assessing product, manufacturing process and supplying chain from an environmental (e.g. LCA, material flows), social (e.g. sustainable livelihoods, ecological footprint) and economic aspects (e.g. cost/benefit analysis, modelling). Singh et al. [6] provided an overview of sustainability assessment methodologies, categorized as indicators/indices, product-related assessment and integrated assessment. Despite having many assessment tools being used, only a few provided an integral approach that took into consideration environmental, economic and social aspects. They also concluded that while it may be possible to combine several different methodologies to ensure that all aspects are taken into consideration, it is not as effective when considering sustainability in its entirety as it is easy to miss the interlinkages and dynamics within a system.

Similarly, Boer et al. [7] conducted an extensive review of sustainability assessment methods and concluded that most indicators used were unbalanced and too qualitative to be applied effectively, as well as not always including the social aspects related to sustainability. Taking these points into consideration, Boer et al. [7] developed a sustainability assessment model (SAM), specifically devoted to the implementation of SMC, which involved developing environmental, social and economic indicators that are able to evaluate sustainability considering the solution space as a whole, i.e. considering the manufacturing system and supply network and looking at a single unit of product in order to foster an immediate perception of the burden set to the environment, society and economy connected to the final act of buying. As part of the assessment model, environmental, economic and social indicator calculation formulas, based on the LCA methodology, were also developed to calculate the impact potential, providing a concrete way to assess impacts and to be transparent.

Collado-Ruiz et al. [8] argued that the LCA method has limited usefulness during the early design stage of a product and can in fact limit designers' creativity and innovation potential; additionally when LCA results can be available, it tends to be either too late or too expensive to make major product changes. The LCA is a complex process requiring detailed information about a product that is not always available at the early design stage and therefore relies on previous products to estimate data required for the assessment (hence limiting a designers' potential) [8]. They suggest instead to infer common environmental behaviour based on similar products (with common functions, parts or properties) – defining the relevant life cycle stages based on past information from previous products' environmental performance, which can be performed at the early design stage.

2.2 *Mass Customization*

MC is a contemporary production strategy aiming to satisfy all individual customers' needs at the price of typical mass production. This strategy allows to push industries to survive against the global competitive pressure, developing new methods and technologies, mostly oriented towards high personalized products [7]. The emergence of MC is also due to the current manufacturing era [9]. Nowadays the product demand is simultaneously very high and strongly differentiated, which results into a fluctuating behaviour coupled with a high unpredictability since a considerable number of product variants are required for satisfying the specific needs of each customer.

The term MC has been firstly defined in 1987 by Davies [10] as a strategy for the provision of personalized product and services simultaneously treating individual customers. This definition has been refined several times adding new concepts and interpretations. Later on, MC gained popularity also due to process and technological innovations. In 1993, Pine et al. [11] defined MC as an industrial perspective able to provide a tremendous variety and individual customization at reasonable prices. This wave of popularity promoted a considerable number of academic articles and industrial experiments, which allowed a continuous evolution and refinement of the concept. For instance, according to Chen et al. [12], MC can be described as a production paradigm that tries to combine the benefits of craft production of pre-industrial economies and mass production of the industrial economies, aiming to deliver products and services that best meet individual customers' needs with near mass production efficiency.

Piller has provided a comprehensive definition, underlining some key drives of MC, in 2004: "Mass Customization refers to customer co-design process of products and services, which meet the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes. As a result, the costs associated with customization allow for a price level that does not imply a switch in an upper market segment" [13].

This new production strategy, in order to be applied, needs specific conditions. In fact, not all type of industries can implement such strategy, in which success is strongly dependent on processes and product characteristics [14]. Walczac identified that assembly processes with low-medium production volume with many variants are the most suitable ones (e.g. clothing, computer manufacturing, mobile telephone, etc.). Fogliatto et al. in 2012 [15] while providing a wider review about MC success factors and enablers also highlighted the main steps required for generating and processing MC orders: building product catalogues, configuring customer orders, transferring orders to manufacturing, and manufacturing customized orders. In this context, Boer et al. [7] in alignment with Piller [13] specified four items needed to apply MC strategy: (i) customer codesign process, which meets (ii) the need of each individual customer, within (iii) a stable solution space representing the potential product configurations, the production system and the supply chain, and (iv) an adequate price based on cost and the premium price that customers are willing to pay for customized products.

In conclusion, one essential element that differentiates MC from mass production is the customers' active involvement in the value creation process in the former. In fact, in MC, customers are no longer passive recipients of products or services that are designed and produced for a nominal customer. Instead, each customer has his or her individual identity and provides key inputs in designing, producing and delivering the product or service based on his or her individual preferences [16].

2.3 Mass Customization and Sustainability

Nowadays, the most recognized definition of sustainability concept is that provided in 1987 by the Brundtland report [17]: "to meet the needs of the present generation without compromising the ability of future generations to meet their own needs". In 1994, Elkington further formalized the sustainability concept through the triple bottom line [18] framework where what is sustainable stays at the intersection among all the three dimensions:(i) environment, which encompasses the protection and conservation of the ecosphere; (ii) society, which includes the respect of the needs of individuals considering their well-being; and (iii) economy, which focuses on the importance of stable economic growth using resources in order to allow the business to continue over a certain number of years.

After the emergence of MC, some questions arose regarding how MC products can be sustainable and if MC could foster a more sustainable way to produce. The relation between MC and sustainability has been discussed conceptually in the research field, especially focusing on economic and environmental performances [19]. In order to evaluate how MC affects sustainability in a firm, several studies have been conducted in recent years also exploring how sustainability frameworks can be developed to evaluate MC sustainability performances as well as which business models can be implemented for the integration of both strategies [20, 21].

Can a MC product be sustainable? This is the question that Ditlev et al. in 2013 [22] tried to answer. They analysed the implication of using MC in three phases (production, use and end of life) concluding that there is not a causal relationship between MC and sustainability but there is the opportunity to integrate several factors that can enhance sustainability performance while developing MC products. Pourabdollahian et al. [21] evaluated the environmental performance of MC business models taking information from the literature. Depending on the company and the industrial sector analysed, the authors also identified challenges and problems of the potential impacts of MC enablers (postponement, modularity, suppliers' integration, etc.) on sustainability. Hankammer and Kleer [23] assessed the sustainability potential of MC as a particular example of collaborative value creation for the specific case of degrowth business models. They outline that, especially the build-to-order idea, the potential upgradability and the stronger involvement of customers constitute enablers for fostering sustainability through MC.

In order to take into account all possible sustainability implications while producing MC products, a dedicated sustainability framework has been developed by Bettoni et al. [24]. In this study, the attention is particularly paid to the design phase of a product, where the decisions taken by the designers are influencing most of the sustainability impacts. The framework includes guidelines about how to carry out each step of the design considering the product but also the manufacturing system and the supply chain needed to produce and distribute it; the framework has been conceived in a way that both mass customization level and sustainability are enhanced at the same time [25]. In addition, the study focuses on the development of suitable sustainability indicators that can guide the co-design of the MC solution space. Continuing this topic, Boer et al. [7] developed a MC assessment model that is meant to evaluate the sustainability of a MC product through a wide set of indicators that are covering all the three sustainability areas along the entire solution space life cycle. This assessment model allows to calculate the values of the selected environmental, economic and social indicators for the MC solution space; thus, all the potential variants of the personalized product will be weighted according to the relative frequency of choice of each customizable option. The authors present a real case belonging to furniture industry where the assessment model has been applied. The MC sustainability framework has been revised and used to map all useful features and to show how to build a viable business model and the skeleton of the solution space [24]. Moreover, Pourabdollahian et al. [26] described different impact factors along the life cycle of MC products on sustainability compared to mass production. Finally, a couple of studies shed light on the co-creation phase of MC and possibilities to foster sustainable consumption through MC [20, 27, 28].

Considering the literature analysed, it is not possible to state if MC could lead to a more sustainable manufacturing approach since many authors agreed that it is highly depending on the type of product or service [7, 29, 30]. What it has been recognized is that, given the great amount of possible product variants, methodologies and tools are needed to enable a reliable but also fast and simple assessment of the sustainability impacts generated by mass-customizable products [24].

2.4 Requirements for Environmental Assessment Methods in the Context of Mass Customization

As already presented in Sect. 2.3, the environmental assessment of a MC product requires further effort compared to a mass-produced product since a MC product is indeed constituted by all its possible variants; thus, a great amount of possible combinations of elements has to be managed. In order to estimate the environmental impacts of each of these elements, LCA and LCC methodologies can be applied. This requires collecting a considerable amount of data such as cost, weight, material characteristics, production processes, transportation means, etc.

Indeed, two possible approaches can be applied for the sustainability evaluation of MC products, depending on the assessment scope. On the one hand, the model proposed by Boer et al. [7] is meant to calculate the sustainability indicators for the mass-customizable product, thus including all its possible variants. This approach is suitable when the scope of the LCA is to evaluate how much the entire solution space is sustainable. On the other hand, it is possible to perform an LCA on every single product configuration (i.e. the MC product), when only a small number of product configurations have to be compared to promote the selection of the most sustainable one [31]. For configurators with greater variation, however, performing an LCA for each possible product combination is far too time-consuming and resource intensive [32]. In order to facilitate a combinatorial evaluation process at the same time providing environmental impacts for each product combination, the environmental assessment method requires to adopt the same modular nature of MC and segregate the product into its separate elements. Hence, as each element is added to form a product, similarly the impacts can be summed as well. The LCA-based methods require also to consider the life cycle stages of the product and how these interact with individual elements. At some stages, the product has to be assessed in its single parts (e.g. production of a frame or recycling of a copper cable), whereas in other stages the whole product is characterized by a single impact (e.g. energy consumption during the use phase). Furthermore, the MC business may choose to offer services that can influence the life cycle impact, such as a take-back service that can ensure the reuse or a more efficient recycling of a given physical product. Services behave differently when it comes to their environmental impact assessment as they rather act on one or more life cycle phases than on product parts. The environmental assessment approach selected for MC would need to consider these type of products or services as well.

According to Feitzinger and Lee, one of the benefits that brings modular product design to MC is the maximisation of standard components which also reduces the total number of components [33]. Similarly, such benefit can be applied to the assessment approach. By selecting and categorizing data on components that are standardized by either their application for different products or processes, the environmental assessment method can be applied more efficiently for MC than for businesses with higher end product variety.

3 SMC Excel Sustainability Approach (SESA) for the Environmental Assessment of Sustainable Mass Customization

We apply SESA in this work to the specific case of TV sets; for in this kind of products, the needs of each individual customer are satisfied through modularity; in fact, aesthetics, fit and comfort and functional features are addressed through the use of different modules that can be put together in order to satisfy the customer wishes. The TV modular system thus requires a flexible and combinatorial method, the SESA, that allows to assess the impact of independent components using a matrix structure and then calculate global impacts for each solution that can be generated by the customer during the codesign phase, using, for instance, a configurator. The cited matrix structure is known as the stable solution space [7] of the company and includes the description of all the possible components that constitute the mass-customizable product, defining also the required production processes and the supply chain-related data.

In order to allow the sustainability evaluation of the TV in a quantitative way, along its whole life cycle and to make available a fast but reliable assessment to the customer so that the environmental impact is introduced as an evaluation parameter, the SESA has been developed considering the following characteristics.

Life Cycle Oriented, Based on LCA Methodology The environmental impacts are evaluated along the whole life cycle of the components/product, starting from the production of raw materials, passing through manufacturing, use and maintenance phase and concluding with the end-of-life (EoL) phase. This approach is meant to avoid problem shifting and assure that environmental problems are not moved from one phase to another one or from an environmental compartment to another one. In order to address this requirement, life cycle assessment (LCA) method has been applied since it is considered as one of the most thorough and accurate methods among the environmental scientific community.

Screening LCA Approach The high complexity of the TV product combined with the fact that the solution space can produce several combinations of TV variants would make a full-scale LCA merely impossible within the SMC Excel project timeframe. It is thus important to clarify that the assessment proposed by the SESA is based on the LCA methodology but does not represent a full-scale LCA in the traditional sense. A full-scale LCA requires a considerable amount of time, data and resources, especially considering the aim of the SESA that is to compare product variants. The SESA thus has been based on screening LCA approach, allowing a preliminary evaluation of the product performances in order to understand the system hotspots but at the same time enabling the comparison between different product configurations. In screening LCA simplification and assumptions are made when specific life cycle inventory (LCI) data are not available; moreover, the life cycle impact assessment (LCIA) is estimated also relying upon generic data available in databases and the literature. The exploitation of screening LCA approach is also justified by the fact that the use phase of TVs is recognized as the most energy-intensive and environmental-impacting lifecycle phase, followed closely by the material production phase [34, 35]. Thus, in SESA a special attention is devoted to energy consumption data and material information, while the production/assembly and the transportation phase are those where most of the simplifications have been introduced.

Delta Evaluation Approach Since the scope of SESA is the comparison between similar products (they all belong to the same solution space), and considering the screening LCA perspective, a delta evaluation approach has been introduced in order to further ease the evaluation of the single product configuration. The idea behind this approach is showing only the impact variations. Therefore, it is not necessary to perform a complete LCA of the product but only focus on the analysis of the elements and features that both enable the TV personalization and generate environmental impacts (for instance, a software component is adding functionalities but is not introducing additional impacts if it does not require extra energy). The delta approach is a core concept of SESA and is described in detail in Sect. 3.1.

GWP Oriented but Extendible to Other Sustainability Areas LCA is commonly addressing the environmental area of sustainability covering different environmental compartments (air, soil, water, human being, etc.) and environmental problems such as global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), human toxicity potential (HTP), Ozone Depletion (OD) or Ecotoxicity Potential (ETP). In order to simplify the communication to the customer of environmental performances of the product variants, the assessment is restricted to the calculation of the GWP index, expressed in the unit kg CO_2 equivalent. This indicator is nowadays well recognized, and it has become of common use in environmental communication. Currently, only the environmental aspects of sustainability have been considered in SESA, but the approach, thanks to its structure presented in Sect. 3.1, can be expanded to also address the economic area, through LCC or the social one through S-LCA.

3.1 Scope and Methodology of the SMC Excel Sustainability Approach (SESA)

The main objective of the proposed assessment framework is to enable the customer to compare in terms of environmental impacts the configured product with a benchmark one that has been identified as a reference. This will be performed through a calculation engine directly connected to the configurator, so that the user can determine the impact of its choices, and to a LCIA database that contains the environmental impact information regarding the TV set components and features. During the configuration process, the configurator provides customers with the sustainability information in terms of the GWP characterization factor, which is expressed in kg CO_2 equivalent. As briefly stated in the previous section, this methodology is mainly based on the delta evaluation approach. A detailed description of the steps characterizing this approach is presented hereinafter.

Benchmark selection A baseline "standard" TV is chosen as a benchmark. The standard model has been chosen by the TV manufacturer VESTEL to serve as a reference point for a typical TV. The standard configuration features are reported in Table 1, where different aesthetics and functional characteristics are depicted. The reference use scenario has been defined as 6 years of lifetime, with a use time of 4 hours per day. A year is assumed to have all 365 use days without holidays. Concerning the transportation scenario, only the one bringing the assembled product from Manisa, Turkey (VESTEL production site), to München, Germany (customer), has been considered. All other transportation routes in the life cycle are neglected as specific data was not available.

Prioritization of the LCA analysis In order to select components to be included for the analysis using SESA, a structure that is meant to prioritize the interventions has been defined and depicted in Table 2.

Three different steps have been identified. In Phase I, the impact related to the components and features that are variable within the solution space and that are LCA relevant (in the sense they cause environmental burdens) is calculated individually.

Table 1 Standard configuration overview

Standard Configuration			
Screen size	49 inches	Smart TV	No
Resolution	UHD (3840 × 2160 px)	PVR-ready function	Yes
Energy label	A+	Wireless display	No
Colour of material	Black	Warranty	Standard warranty (2 years)
Frame	Plastic	Take-back service	No
Stand	Plastic	Production offsetting	No
Remote control	Yes	Packaging	Standard packaging
Satellite receiver	Yes	Delivery	Standard delivery
Lighting unit	No		
Charging unit	No		
Sound unit	No		

Table 2 Overview of components categorized in the scope of environmental assessment

Phase I	Phase II (Baseline)	Excluded from env. assessment
Variable LCA solution space: components that are variable and LCA relevant (e.g. frame material)	*Invariable LCA solution space:* components that are LCA relevant but not variable (e.g. motherboard, PCBs, etc.)	*Non-LCA solution space:* components that are variable but not LCA relevant (e.g. software that does not influence or, to a negligible way, the overall kg CO_2 eq. value
Screen size (energy) Screen resolution (energy) Energy label (energy) Frame (material) Stand (material) Remote control (material) Lighting unit (material) Wireless charging unit (material) Bluetooth speaker (material) PVR ready (energy) Warranty (material) Take-back service (material) Offsetting production (material) Packaging (material) Delivery (material)	Printed circuit boards Capacitors, resistors, etc. Electronic connectors Bolts and screws Cables Display module Backlight (LED)	Satellite receiver Smart TV Wireless display

Some of the features are provided by physical components, such as the TV frame or the support system; others are more intangible elements such as the energy class of the TV or the screen resolution. The ensemble of these components is called variable LCA solution space. In Phase II, the impacts related to the other elements belonging to the solution space that are LCA relevant but that do not change when passing from a configuration to another one are assessed. These components are thus the ones which constitute the baseline and are represented by a single value for each life cycle phase (e.g. baseline value for transport: 6.13 kg CO2 eq.). The baseline value is the average GWP impact obtained from three LCA studies on LED TVs [34, 36–38]. Some elements that have negligible LCA impact are excluded from the SESA approach but remain included in the configurator because they can influence the level of MC as well as customer satisfaction.

LCI of the Variable LCA Solution Space For each element included in the variable LCA solution space, the related LCI data has been collected in order to estimate the environmental indicators. For physical components, LCI information includes the material type and their quantity, the production processes and the EoL treatments undergone; for intangible elements, inventory data are, for instance, represented by the energy consumption of the TV function/characteristic. LCI data has been based on the ecoinvent database and literature, while product-specific data has been provided by VESTEL.

LCIA of the Single Components Starting from the LCI data collected in the previous phase, and exploiting LCIA database such as ecoinvent and PlasticsEurope, the calculation of the GWP indicator has been performed for each feature included in the SESA solution space. The GWP indicator, expressed in terms of kg CO2 equivalent, has been evaluated considering the CML2001 methodology.

For physical elements, the computation has been performed along the whole life-cycle of the item, thus considering all the related processes, from material extraction to end of life, passing through manufacturing, assembly and transportation. The calculation of the contributions to GWP indicator has been performed through the following formula:

$$Id_{o,c} \times CF_o = GWP_{o,c}$$

where:

- $Id_{o,c}$ is the inventory data of the o-th operation performed on the c-th component included in the variable LCA solution space
- CF_o is the characterization factor the o-th operation retrieved from the LCIA database cited
- $GWP_{o,c}$ is the contribution to the GWP indicator related to the o-th operation performed on the c-th component

For instance, the material extraction coefficient for the cardboard used for packaging is CFo = 0.65 kg CO2 eq./kg (where o is thus the extraction operation of cardboard), while the Ido,c of the packaging provided by VESTEL for the standard packaging for a 49” TV weights 1.19 kg, so the GWP related to the cardboard extraction is about 0.78 kg CO2 eq. The impact of most of the non-physical elements is calculated applying a similar formula, even if they are characterized in a different way specifying the consumed electrical energy expressed in kWh (Ide), and by the characterization factors for each electricity mix considered (CFe). The GWPo,c computed is stored in a repository that will be exploited by the configurator engine for the calculation of the total delta GWP.

Product variant delta GWP calculation Once the single elements have been characterized by the LCI, an assessment model has been developed in the configurator so that the impact in terms of GWP of each element is calculated. At the end of this process, the sustainability engine sums up all the variations so that a global delta GWP is estimated.

3.2 Data Collection and Assumptions

This section is meant to briefly present the data gathering activities that have been performed in order to complete the LCI and LCIA phases for the variable LCA solution space so that the related impact could be calculated through the formula mentioned above. Moreover, the paragraph also introduces the assumption applied to model the components and TV set life cycle. In the following, different subsections are reporting the information collected regarding raw materials (extraction and processing), manufacturing processes, delivery, use phase and end-of-life scenarios.

Material Extraction, Production and Processing LCI and LCIA Data
Two elements are needed for the computation of the GWP indicator: the inventory data, thus the type of the material constituting the element and its weight, and the related characterization factors. Table 3 reports an excerpt of the main components included in the variable LCA solution space with the inventory data cited.

As already stated, the variable LCA solution space contains both physical and non-physical elements that are relevant for LCA. Software elements that are not generating impacts have been thus excluded from this list.

Table 4 shows an excerpt of the LCIA data retrieved from available database (indicated in the table) and concerning the impact generated by the extraction of materials for the different elements constituting the variable LCA solution space. Table 4 moreover indicates if the considered dataset already includes transportations and the impact data of the electricity mix considered for the use phase. The same LCI collection process and electricity mix were applied to the manufacture and assembly processes.

Use Phase and Energy
The energy consumption is mainly influenced by screen size (49″ or 55″), energy label (A or A+) [39, 40] and resolution (full HD or UHD) [41]. The combination of these six variables gives eight possible combinations as shown in Table 5. The same table includes the power consumption and the energy consumed into the use scenario already cited (6 years, 365 days per year, with an assumed use of 4 hours per day) [42]. Moreover, the energy consumed has been translated into equivalent CO_2 emissions according to the electricity mix defined for the use phase as shown in Table 6.

Table 3 Excerpt of the variable LCA solution space

Variable	Variable	Solution space final		Weight
				kg
	Screen_0	Combination 0	49″, UHD, A+	9.7
	Screen_1	Combination 1	49″, Full HD, A+	9.7
	Screen_2	Combination 2	49″, Full HD, A	9.7
	Screen_3	Combination 3	49″, UHD, A	9.7
	Screen_4	Combination 4	55″, UHD, A+	11.7
	Screen_5	Combination 5	55″, UHD, A	11.7
	Screen_6	Combination 6	55″, Full HD, A+	11.7
	Screen_7	Combination 7	55″, Full HD, A	11.7
Material_49	Material_49_1	Casing (49″)	Plastic 30% recycled material	1.57
	Material_49_2		Bioplastic	1.13
	Material_49_3		Aluminium	2.17
Material_55	Material_55_1	Casing (55″)	Plastic 30% recycled material	1.74
	Material_55_2		Bioplastic	1.2
	Material_55_3		Aluminium	2.412
	Stand_1	Wall mount and stand options	Plastic stand	0.19
	Stand_2		Table top metal stand	1.5
	Stand_3		Wall-hanging apparatus	0.116
	Stand_4		Vdrop stand	3.25
Remote	Remote_yes	Remote control	Remote control	0.089
	Remote_no		Smart APP Remote Control	_

(continued)

Table 3 (continued)

Variable	Variable	Solution space final		Weight
Satellite	Satellite_yes	Satellite receiver	Yes	_
	Satellite_no		No	_
Lighting	Lighting_no	Lighting unit	No	_
	Lighting_yes		Yes	0.12
Charging	Charging_no	Wireless charging unit	No	_
	Charging_yes		Yes	0.35
Sound	Sound_no	Bluetooth sound speaker	No	_
	Sound_yes		Yes	0.45
Warranty	Warranty_1	Warranty	Standard warranty	_
	Warranty_2		Extended warranty	_
	Warranty_3		Premium warranty	_
Takeback	Takeback_no	Take-back service	No	_
	Takeback_yes		Yes	_
Offsetting	Offsetting_no	Offsetting	No	_
	Offsetting_yes		Yes	_
Packaging_49	Packaging_49_1	Packaging (49″)	Standard packaging	1.985
	Packaging_49_2		Packaging ECO	2.385
Packaging_55	Packaging_55_1	Packaging (55″)	Standard packaging	2.77
	Packaging_55_2		Packaging ECO	3.2
Delivery	Delivery_1	Delivery	Standard delivery	_
	Delivery_2		Express delivery	_
	Delivery_3		CO2 neutral delivery	_

Table 4 Excerpt of the LCIA data regarding material extraction

Material/component	Ref. unit	Dataset	Coefficient (eq. kg CO_2)	Includes transport?	Database
Aluminium	kg	Market for aluminium, primary, ingot, IAI area, EU27 and EFTA	9.3864	Yes	Ecoinvent
General-purpose polystyrene (GPPS)	kg	PlasticsEurope Eco-profile GPPS_HIPS 2013–04	2.2500	No	PlasticsEurope
Cardboard	kg	Corrugated board base paper, kraftliner, at plant	0.65838	Yes	Ecoinvent
EPS	kg	PlasticsEurope Eco-profile EPS 2015–02	2.37	No	PlasticsEurope
Case (PC/polycarbonate)	kg	Market for polycarbonate	7.8648	Yes	Ecoinvent
Rubber keypad (TPE, thermoplastic elastomer, e.g. Styroflex)	kg	Market for latex	2.7073	Yes	Ecoinvent
Speaker box (two units): PC (60%) + ABS (40%); Magnet (two units)	kg	60% PC + 40% ABS	6.529	Yes	PlasticsEurope + ecoinvent
PLA	kg	Market for polylactide, granulate	3.2561	No	Ecoinvent
ABS	kg	Market for acrylonitrile-butadiene-styrene copolymer	4.5253	Yes	Ecoinvent
Low-density PE (EPE)	kg	PlasticsEurope Eco-profile PE 2014–04	1.87	No	PlasticsEurope
PA 6	kg	Market for nylon 6, GLO	9.356	Yes	Ecoinvent
Frame	kg	Market for aluminium, primary, ingot, IAI area, EU27 and EFTA	9.3864	Yes	Ecoinvent

Table 5 Power consumption and GWP calculation of the possible TV combinations

	Power	Use for 1 year (365 days), 4 h per day	Use for 6 years (365 days), 4 h per day	Coefficient: electricity, low voltage, production, UCTE	Total (use for 6 years)
	(W)	(kWh)	(kWh)	(kg CO_2 eq.)	(kg CO_2 eq.)
49″, UHD, A+	78.87	115.15	690.89	0.51	349.34
49″, full HD, A+	60.67	88.58	531.45	0.51	268.72
49″, full HD, A	81.98	119.70	718.18	0.51	363.14
49″, UHD, A	106.58	155.61	933.63	0.51	472.08
55″, UHD, A+	97.51	142.37	854.23	0.51	431.93
55″, UHD, A	132.82	193.92	1163.52	0.51	588.32
55″, full HD, A+	75.01	109.52	657.10	0.51	332.26
55″, full HD, A	102.17	149.17	895.02	0.51	452.56

Table 6 Electricity mix for use phase

Material/component	Ref. unit	Dataset	Coefficient (eq. kg CO_2)	Includes transport?	Database
Electricity mix	kWh	Electricity, low voltage, production, UCTE	0.5056	No	Ecoinvent

End-of-Life (EoL) and Take-Back Service Scenario

Concerning the end-of-life scenario, in line with recent statistics at the European level, it is assumed that about 45% of the product returns into the recycling stream [43–45]. With dedicated take-back service, it is expected that up to75% percent of the product would be recycled. Table 7 presents an excerpt of the LCIA data considered to calculate the impacts generated by the different EoL scenarios.

In order to calculate the EoL coefficients, according to the end-of-life recycling approach suggested by the Declaration by the Metals Industry on Recycling Principles [46], the impacts of the recycling processes and the GWP credits gained thanks to recycling (since it avoids the extraction of raw material) are summed in proportion of the envisaged recycling rate.

The following comparative validation process will show the correlation between the SESA results with the results of a full-scale LCA based on the standard model configuration of the TV. Additionally, the take-back scenario is presented for both cases in order to analyse the difference on the overall system environmental impact with and without this service.

Table 7 Excerpt of the LCIA data for EoL scenarios

Material/component	Dataset (ecoinvent and PlasticsEurope)	Coefficients	Scenario 75% (eq. kg CO_2)	Scenario 45% (eq. kg CO_2)
Aluminium	Market for aluminium, primary, ingot, IAI area, EU27 and EFTA	9.39	−6.48	−3.87
	Treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter, RER	0.73		
	Market for waste aluminium	0.04		
Cardboard	Market for carton board box production, with gravure printing	0.66	−0.47	−0.26
	Market for waste plaster-cardboard sandwich	0.01		
	Treatment of waste packaging paper, municipal incineration	0.06		
Polycarbonate	PlasticsEurope Eco-profile EPS 2015–02	7.86	−5.44	−2.98
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Polystyrene (HIPS)	PlasticsEurope Eco-profile GPPS_HIPS 2013–03	2.43	−1.36	−0.54
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Polystyrene (GPPS)	PlasticsEurope Eco-profile GPPS_HIPS 2013–03	2.25	−1.23	−0.46
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Plastic (PC (60%) + ABS (40%))	PC (60%) + ABS (40%)	6.53	−4.43	−2.38
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
EPS	PlasticsEurope Eco-profile EPS 2015–02	2.37	−1.32	−0.51
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
PLA	Market for polylactide, granulate	3.26	−1.98	−0.91
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Rubber keypad	Market for latex	2.71	−1.57	−0.66
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		
Plastic (PC 30% + ABS 20% + PE 50%)	PC 30% + ABS 20% + PE 50%	4.16	−2.66	−1.32
	Plastic recycling	0.38		
	Market for waste plastic mixture	0.70		

4 Comparative Validation of SESA with a Full-Scale LCA

Within the framework of the SMC Excel project, a full-scale LCA was performed focusing on the standard configuration of the TV presented in Sect. 3.1. The full-scale LCA study includes practically all the components and specifications that were applied for the SESA environmental assessment approach. As can be seen in (Fig. 1), the impacts per life cycle phase only differ minimally in both studies. Major discrepancies appear for the production stage which in the full-scale LCA is encompassing both extraction and production stages, while the SESA approach applied an independent environmental assessment for both phases, resulting in a higher value of GWP indicator. Looking at the graph and considering all life cycle phases, it can be noticed that the overall impact in kg CO_2 equivalent is not much different; with SESA the total GWP impact of the TV is 616.23 kg CO_2 eq., while the full-scale LCA displays a slightly lower impact of 572.39 kg CO_2 eq.

The impact of the take-back scenario presents a minor difference for both environmental assessment methods, acting in a proportional relation to the impact of the disposal phase. Nevertheless, in this study only a change in the recovery of materials is considered so that further effects on, for example, secondary impacts on recycling processes or disassembly are disregarded. We conclude that both methods present similar results, which indicate that the SESA approach performs with considerable accuracy and may be applicable for MC.

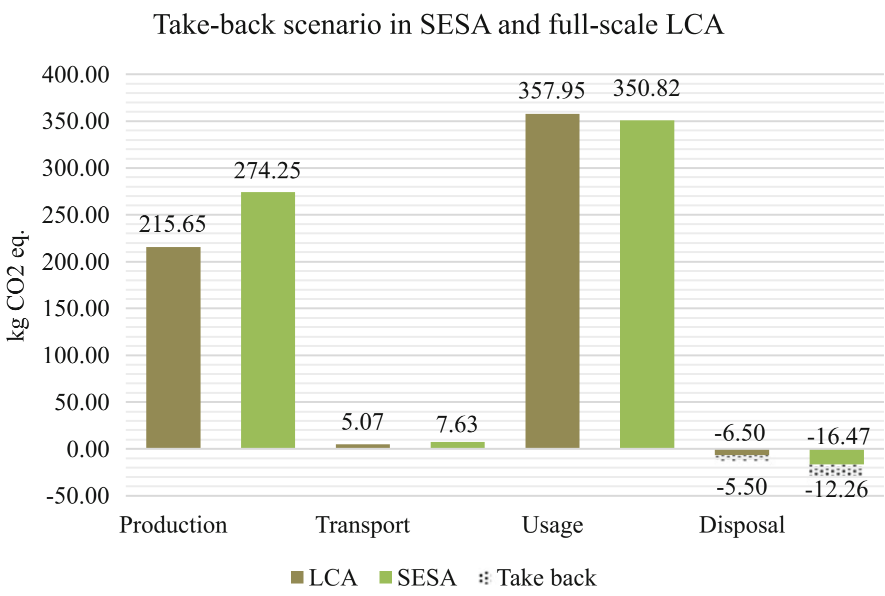

Fig. 1 Comparison between the SESA approach and the full-scale LCA on the standard configuration

5 Know-How and Communication

The proper communication through the configurator about the sustainability impact of the products or services offered is imperative for influencing customer behaviour. Customers need to be informed on the content and implications as well as the benefit of selecting a sustainable feature. Considering that information on environmental impacts is often difficult to associate with daily life experiences, it could be represented through a value-based approach. An example would be by comparing the impact with an amount of km driven by a car (gasoline value) as also applied by the Restart Project for their Fixometer [47]. Creating a value link between the effect of km driven and of TVs provides the user with an idea on the proportionalities of environmental impacts. Hendriks et al. also formulate such an approach in cost terms as proposed in their model of eco-cost/value ratio (EVR) [48]. Furthermore, through a survey performed during the SMC Excel project, it was found that providing a sustainable configuration as a starting point fosters more users to keep the sustainable features that are already preset by the system. Thus, the customers buying preferences can be as well influenced or "nudged" towards a more sustainable consumption on a more unconscious level.

One of the main traits of MC is the co-creation process [13]. This is basically the pivot at which business and customer interact and influence each other's practices, may it be in respect to production and design or consumers' lifestyle choices. But consumer and business are not isolated in this synergy as also other industries, and in a greater sense, the market of the MCs' sector can be influenced. The selection of materials has a repercussion on processes as well as suppliers and, therefore, also on the material extraction industry. Services may even influence post-production life cycle phases of the product, including the related industries to TVs during use phase (e.g. energy provider) and disposal processes (e.g. recycling of EEE). For these reasons, the co-creation process in SMC business models becomes a shared responsibility between the business and consumer for the inclusion of sustainable products in the market. The customer becomes less a subject but rather an actor in MC. Consequently, the customer may also be accountable for the success or failure of the sustainable development in that market, provided that the customer is also receiving in a suitable form the right information on the sustainable performance of the product [49]. As stated by the World Business Council for Sustainable Development (WBCSD) report, consumers are becoming more aware and increasingly concerned about environmental, social and economic issues and more willing to act on these concerns [50]. Hence, it is even more important that information on sustainable features is provided with reliable data and clear communication. Since customers become more aware, they also become more sceptical if information is not accurate, or conversely, they might receive the wrong information and think that it is sound science which leads to an erroneous state of awareness. The latter occurs in situations where companies massively underline only the product characteristics that improve sustainability, whether or not these improvements are significant looking at the overall product assessment, in order to advertise the product as truly sustainable; this phenomenon is also known as "greenwashing" [51]. The high problematic resulting from greenwashing is that it creates mistrust among consumers towards businesses and, consequently, reduces the effect of a productive co-creation mechanism that could lead to a sustainable development with the involvement of all stakeholders.

6 Conclusion

6.1 Key Findings and Major Contributions

This work proposes the adoption of SESA, an approximated sustainable approach based on delta LCA evaluation, developed for providing realistic information about product environmental sustainability to consumers involved into the codesign process of MC products. The approach allows focusing on the most significant impacts of the product and its life cycle phases as well as obtaining environmental data on all variable components and product combinations. The reliability of the provided sustainability information is evaluated confronting the results of SESA with those of a full LCA while evaluating an MC TV solution space. The analysis proved that SESA allows to obtain reliable results of environmental impacts and may be applicable for MC business models with a sustainable business approach.

SESA has been developed and kept simple in order to be continuously updated at reasonable costs while evaluating solution spaces that tend to become increasingly complex and to rapidly change, due to the continuous developments of new features and variants especially in sectors like the consumer electronics where the pace of innovation is quite high.

6.2 Limitations and Further Research

The approach has been partially validated considering a single use case and a unique sustainability indicator. Additional work is required for investigating the reliability of SESA in comparison with more expensive and complex full LCA on a broader sample of use cases and considering a greater variety of indicators. The effect of providing data about various indexes on consumer attitude towards sustainability must be further analysed in order to avoid customer confusion and effectively promote the adoption of sustainable consumption. The analysis of intangible product components and services also needs to be improved in order to identify how they can promote the adoption of circular economy business models [52]. Moreover, in order to decrease the risk of underestimating the impact of services, such as the product take-back analysed in the TV case, their LCA-based estimation has to be done taking a broader perspective and not just focusing on recovery of materials.

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Part IV
Choice Navigation and Customer Interactions for MCP

The Importance of Choice Navigation in Starting Configurator Projects

Ottar Bakås, Lars Skjelstad, Børge Sjøbakk, Maria K. Thomassen, Paul Blazek, and Martina Partl

Abstract Choice navigation can support customers in identifying their own solutions while minimizing complexity and the burden of choice. Product configurators are used as an interactive tool to help customers in this process. For companies aiming to develop a configurator from scratch, there are many hurdles. Particularly for SMEs, there are additional challenges, such as shortage of resources, experience, and knowledge in developing a viable configurator tool. In this paper, we explore the process of designing choice navigation through a product configurator tool. We review existing methodologies and propose a new process model. Empirical data come from a case study of three SMEs embarking on the process of establishing a choice navigation tool. The proposed model is developed in the context of the research project Custom^{R}. The new process model is cyclic and customer-driven and aims to develop need-based configurators (as opposed to a linear, technology-driven, and function-based approach). The paper reports on challenges and success factors from an ongoing configurator development project.

Keywords Mass customization · Choice navigation · Configurators · Customer-oriented

1 Introduction

Both private and industrial customers are increasingly demanding products specifically made to fit their individual needs. And customers are willing to pay for customized products. Studies have found a willingness to pay premiums of up to

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100% within segments such as watches and apparel [1]. The increased value can encompass better fit or function, enjoyment of co-design, perceived uniqueness, and a pride-of-authorship effect [1].

However, customers are not necessarily willing to wait much longer to have their order delivered [2]. This has been labeled the customization-responsiveness squeeze [3]. In addition to delivery time pressure, offering customized products can create challenges in terms of efficiency and profitability of operations.

Mass customization (MC) is a business strategy that addresses the challenge of meeting individual customer needs in a cost-efficient manner. It aims to combine the flexibility and personalization of custom-made products with the low costs associated with mass production [4]. Three core capabilities have been identified to pursue a mass customization strategy [5]. First, *solution space development* focusses on identifying product attributes where customer needs diverge. Second, *robust process design* aims to enhance flexibility in the production system and organizational resources. Third, *choice navigation* should support the customers to define their own solution within the solution space.

Mastering MC capabilities requires a new set of competence and skills from a company. These include flexible manufacturing, improved product development, closer supply chain management [6], and enhanced digital competence of configuration software and virtual prototyping [5].

Acquiring such competences can be more challenging for small- and medium-sized enterprises (SMEs) compared to larger corporations. SMEs often have limited resources in terms of man power, access to skills, and financial strength for investments [7, 8]. SMEs are typically more vulnerable and take a more low-risk approach in MC initiatives [6]. However, SMEs have some advantages. Management is usually informal and hands-on, with clear vision and goals. Many have flat organization and fast decision-making [9], enabling flexibility and responsiveness.

One possibility for SMEs aiming for mass customization is to improve their interaction with customers through *choice navigation*. They can offer products online to wide audience using product configurators. Sophisticated configurators can help SMEs to shift the time-consuming process of identifying the actual demand of the individual to the customers themselves [10]. Further benefits of product configurators include enabling co-design with customers, high salesman productivity, and an organizational memory of product knowledge [11]. However, developing a suitable choice navigation process can be challenging. The company need to understand how their customers think when they are going to design their individual solution. Further, the company must understand *what* is going to be configured (fabrication, assembly, or packaging) and *how* it influences internal processes of order management, manufacturing, and distribution [12]. There is still a need to better understanding the determinant factors of how to develop a successful choice process [13, 14].

The purpose of the paper is therefore *to present a process model for how to design a choice navigation* solution from an SME perspective. The paper aims to answer the question by combining insights from previous studies and practice.

The structure of the paper is as follows. First, the research context and methods used in the paper are described. Then, a literature scan of existing process models for choice navigation is conducted. We also describe success factors and showstoppers in configuration projects. A process model for designing choice navigation is proposed. The model emphasizes frequent customer interaction through the entire process. An empirical study reports from three SMEs that are currently designing their choice navigation solutions. Last, the discussion highlights guidelines for choice navigation design, accompanying the new process model. The paper is concluded with implications for practice and further research.

2 Research Context and Methods

To explore their potential within mass customization, four Norwegian manufacturers have embarked on a joint research project, Custom^R. The main goal of the research project is to develop methods and tools that integrate customer preferences and choice (front-end) with company internal processes (back-end).

A significant amount of software exists that support customer choice navigation. The use of product configurators is widely applied in many industries, especially among large companies. Still, there is a need to better understand the determinant factors of how to develop appropriate product configurators within different contexts [12]. In accordance with the Custom^R research framework [13], a practical roadmap for developing choice navigation tools is expected to be valuable. Choice navigation can help SMEs to improve direct contact with end users and ensure an efficient product configuration process. One of the four project partners already had a configurator in place. The other three companies are smaller and do not have the same resources or experience in developing digital choice navigation tools. So, the question from the three SMEs was: “Where do we start?”

The companies are designing choice navigation within their own specific markets, ranging from wooden windows and doors to high-end kitchen extractor hoods. They share a characteristic of serving both B2B and B2C markets simultaneously. This adds additional challenges when designing their configuration solutions. Their B2B industrial customers are dealers that emphasize efficiency and know the products well. Their B2C private customers have less experience with their products and have other questions and concerns in their specification of a solution.

The research question for this paper is therefore: “How should a process model for designing choice navigation solution look like from an SME perspective?” The paper aims to answer the question by combining insights from literature and practice. The paper is limited to commercial product configuration. It does not address technical configuration tools that are not directly used in choice navigation support.

Research Methods A literature scan of existing process models for choice navigation was conducted. We also identified existing success factors and showstoppers reported from configuration projects. Identified literature, combined with previous experience from practice, was the foundation for an alternative process model for developing a configurator. A set of guidelines complements the process model. An empirical study with three SMEs is the basis for the research and is used to develop and test the process model.

The Custom^{R} project is founded in action research as methodological framework. Researchers and the problem holders (in this case the Norwegian SMEs) collaborate in solving real-life problems. New knowledge is acquired for both parties and fed back to the body of knowledge within research [15]. The case data have been gathered from a series of workshops, semi-structured interviews, and observations at the three companies over a period of 12 months.

3 Designing Choice Navigation

3.1 Choice Navigation

Choice navigation can be defined as the capability to "support customers in identifying their own solutions while minimizing complexity and the burden of choice" [5]. Process satisfaction should be a key objective for choice navigation. In a study of 500 customization firms [16], three criteria were established to measure process satisfaction: usability, creativity, and enjoyment. Additional criteria in the assessment included uniqueness, choice options, and visualization [16].

Online product configurators are often used as a tool for companies to convey their solution space to individual customers. Choice navigation applies at two levels of the customer's decision-making:

1. *Product selection:* selecting the desired product or product family
2. *Product configuration:* customizing the selected product to individual needs

Contemporary sales configurators today often cover both phases. And the application of configurators has spread to a wide range of industries. In the Configurator Database Report 2016 [17], over 1200 international web-based product configurators are identified. However, a significant amount of product configurator projects seems to fail. During 1 year, 204 (19%) of the identified configurators from 2015 had disappeared [17]. Still, the momentum is growing, as 354 (34%) new configurators were included in the same study (ibid).

Two psychological concepts have been found important in designing choice navigation. The *paradox of choice* describes how "too many options can actually reduce customer value instead of increasing it" [5].

Giving customers too much choice creates information overload and a sense of paralysis instead of freedom. This can overburden the customer in his selection process. The decision-making process becomes a problem instead of a positive experience, and the buying decision might be postponed. Focusing on attribute preferences, as opposed to evaluating alternatives, have been found to increase satisfaction and learning [18].

The second concepts have been termed *the anticipated regret* of a choice [19]. The expectation of regret after the decision promotes aversion to actually make the decision [19]. A sales configurator with a high level of focused navigation capability can help the customer limit the set of options to evaluate. More time can be spent to learn about the remaining options where preferences are less certain. Thus, a configurator with a focused navigation enables the customer to be more confident that the chosen solution is the best one [20]. This is in line with Forza and Salvador [12], calling for a simplification of the commercial model by limiting options.

The research from Salvador et al. [5] identified three approaches to develop the capability of choice navigation. These three strategies can help a company mitigate the paradox of choice and anticipated regret of their customers:

1. *Assortment matching*: Software that matches the characteristics of an existing solutions space with the customer's needs and makes recommendations (e.g., Amazon)
2. *Fast-cycle, trial-and-error learning:* Software that help customers define their needs and interactively test and visualize the match (e.g., NIKEiD custom shoes)
3. *Embedded configuration:* Products that "understand" how they should adapt to the customer and then reconfigure themselves (e.g., Tesla adapting to different drivers)

3.2 Existing Process Model for Product Configurator Development

The use of product configurator can provide a range of benefits such as shorter-order lead times, high salesman productivity, improved product specifications and preservation of knowledge, and optimized products [12, 14]. Still, there are not many holistic models with clear descriptions of how to conduct the development of a product configurator [14]. There might not be one best way to carry out the process, as each company has its own characteristics and context. Still, a structured plan for the work can lead to better choice navigation solutions. Three relevant process models have been identified and will be presented.

Haug et al.'s Process Model Haug et al. [14] proposed a process (Fig. 1) consisting of six main steps:

1. Elicitation: a knowledge engineer gathers information from domain experts.
2. Translation of the information to an analysis model.
3. The model is formalized to be more suited for implementation.
4. Information is documented.
5. Implementation: design models are implemented in the selected configurator software package.
6. Documentation is synchronized and updated.

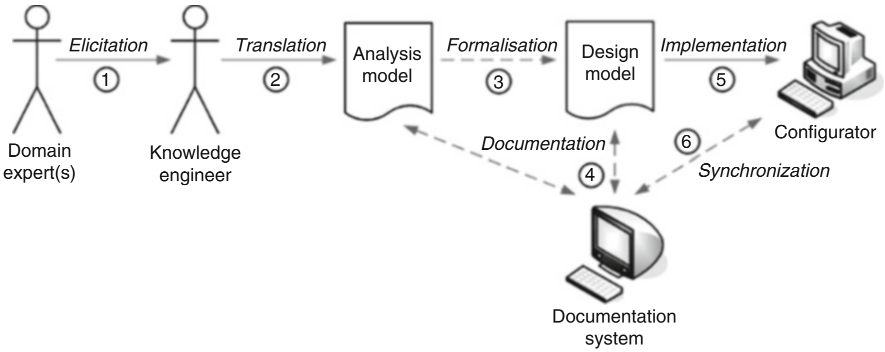

Fig. 1 The process of creating product configurators of Haug et al. [14]

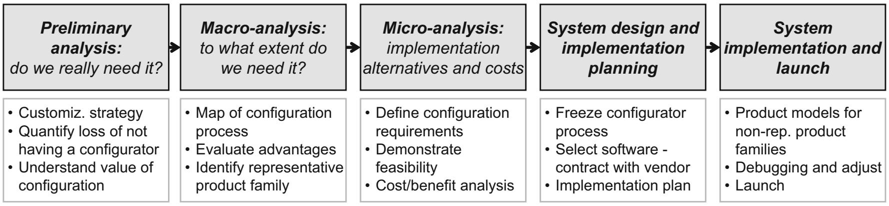

Fig. 2 Steps in implementation process of a configurator, by Forza and Salvador [12]

The model above is a continuation of a stepwise procedure by Hvam et al. [21]. Here, they describe seven phases for the development and maintenance of product configurators. Phase 1 concerns business process analysis of AS-IS and TO-BE processes. In phase 2, product analysis is done of product variants. Phases 3 and 4 involve object-oriented analysis and design, which is programmed in phase 5. Then, the solution is implemented, focusing on training. Phase 7 describes maintenance and development.

Haug et al. [14] describes three main strategies for conducting the overall process model above. These strategies differ in terms of which role is responsible for each step. Letting the configurator software expert model product knowledge directly, without the analysis model, was found to shorten product duration and minimize resource consumption. However, this is not recommended when complexity is high [14].

Forza and Salvador's 5-Step Model Forza and Salvador emphasize that there are many different ways to conduct a configurator development process. Their approach is to describe an overall reference model with five main steps needed to implement a configurator [12] (Fig. 2).

This process starts with a preliminary analysis which aims at deciding whether product customization is sound strategy for the company or not. At the macro level,

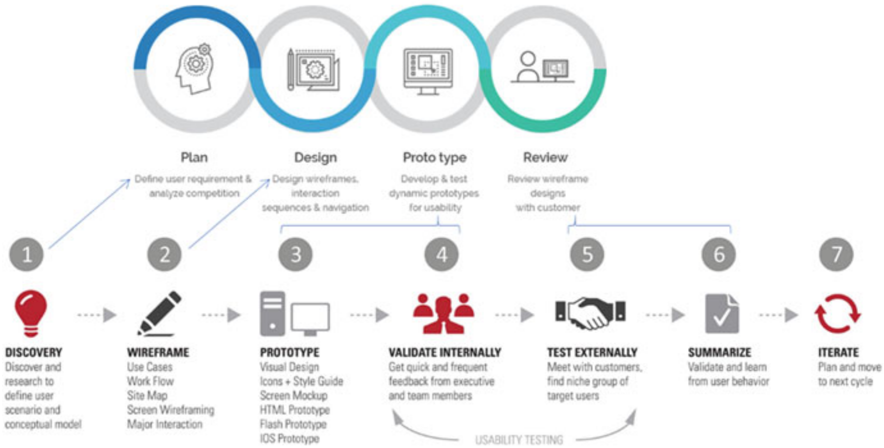

Fig. 3 Example of user-centered design and a lean UX process model, based on Wang [23]

the overall map of the configuration process is made. On the micro level, a more detailed approach to requirements is made. This step should demonstrate feasibility and provide a cost/benefit analysis. In the next step, the configuration process should be fixed, and the company should evaluate and select the software vendor. Lastly, the implementation plan is carried out, and the configurator is launched.

Customer-Oriented Design The customer-oriented approach from lean and agile thinking has highly influenced both the start-up community and the digital world. The approach is based on frequent iterations of development and validation through testing before a product or service is launched to the market. Rapid prototyping and customer feedback are valued over sticking to a fixed plan [22]. Lean user experience (UX) is focused on obtaining feedback as early as possible to steer direction. A team collaborates on finding answers to questions like: Who are the users? What will the product be used for? In which situations? Figure 3 shows a typical user user-centric design process.

3.3 *Success Factors and Pitfalls for Configurator Projects*

A review of reported *success factors* for configuration development processes is given here (Table 1).

A review of reported *pitfalls* for configuration development processes is given in Table 2.

Table 1 Success factors for configurator development processes

Topic	Recommended guidelines for configurator project (Blazek & Pilsl) [24]	Elements of configurator project success (Forza & Salvador) [12]
Define targets	Targets should be defined from the beginning	Top management support Test navigation with sales people
Simplification	Configurators should start slim and stay flexible after launch	Simplify system usage Use prototypes and simulation gradually Automate selectively
Marketing	Existing brands should not overestimate themselves	
Data	Track and analyze customer data	
Involvement		Involve people that have shown interest Provide assistance – train your people

Table 2 Pitfalls factors for configurator development processes

Topic	Project "killers" by Forza and Salvador [12]	Challenges in configurator projects by Haug et al. [14]
Collaboration	Poor inter-functional collaboration (front office-back office)	The configurator must be accepted and used by the organization
Momentum	Excessive workload for key internal people	Keep momentum until configuration is developed to a point where its usable
Architecture	Unreasonable architecture of product families	Ensuring that the configuration covers an adequately large part of the products
Staff	Changes in the roles of personnel	
Standardization	Excessive software customization	

4 Proposed Framework for Designing Choice Navigation

An iterative process model for configuration process for SMEs is here proposed in Fig. 4.

The model consists of five main steps toward choice navigation. The core of the model is the customer of the company. It is the focal point for the process in order to develop a way for the customer to best navigate in the company's solution space. This idea of frequent user testing is a core idea, stemming from agile methods and lean user experience design.

Step 1: Discover and Plan The company researches current trends and shifts in the market. The sales force of the company often has a strong sense of trends and opportunities and should be given an arena to provide this information. The company should reflect on how changes in society and consumer behavior influence your company. A scan of what the competitors are doing in terms of customization can also provide ideas and inspiration. The team needs to establish a project

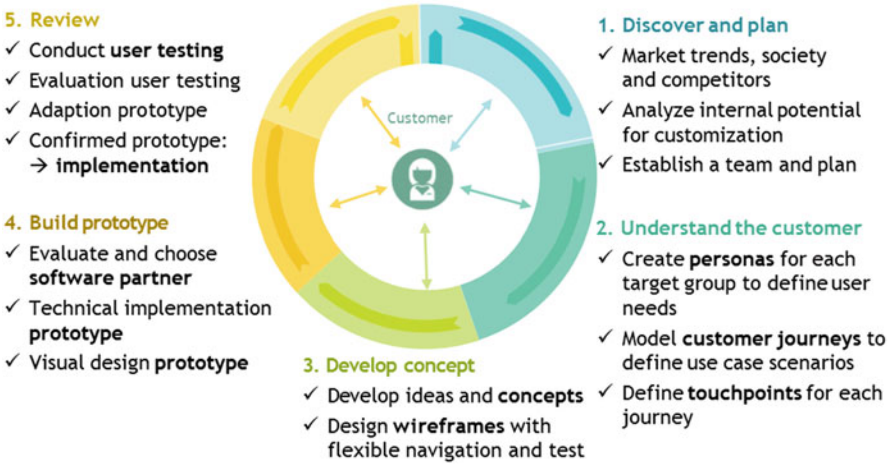

Fig. 4 Process model developed in the Custom^{R} project by cyLEDGE and SINTEF

plan, mandate, and resources. Involve team members that have shown interest in improving the sales process [12]. Top management commitment is crucial to align with strategy and ensure proper support.

Step 2: Understand the Customer It is recommended to use personas as a method to understand your customers thoroughly [25]. In this method, different customer segments are translated to being a specific, but fictional person. This persona is assigned demographics, interests, tech levels, etc. By sketching preferred customer journeys for these personas, the essential requirements for the whole project can be determined, including sales and marketing strategy [24]. Next, each persona is given a customer journey. This journey describes all phases the customer goes through to reach his or her goal. Typical phases are awareness, consideration, research, commitment, and utilization (post-sales). In each step at the customer journey, online and offline touchpoints for the customer with the company are defined.

Step 3: Define Concept The customer journeys and insights from the initial discovery phase are then used to sketch out ideas for navigation concepts. What are the critical concerns of your persona? The concept is then sketched out using simple wireframes. Wireframe is a page schematic that shows a low-fidelity representation of the design. It does not contain graphical elements but uses simple boxes and illustrations to show main elements for information and navigation. Wireframes should then be tested internally and externally. Learning from feedback is used to iterate and refine, until an agreed-upon concept is reached.

Step 4: Build Prototype At this point, a validated concept is in place. If not done already, a software vendor should now be selected. Making prototypes within the software package, your desired commercial software package can be beneficial for implementation. For more information on evaluating and selecting configurator software, see, for instance, Forza and Salvador [12] or Haug et al. [14]. Testing of visual design prototypes with actual customer is critical.

Step 5: Review User testing of visual design prototypes with actual customer is critical. Evaluation of user testing is then analyzed and used as basis for review. This is an iterative process, where the prototype is gradually scaled up toward full implementation. In parallel, training of key staff within the SME should be done.

5 Empirical Data from Applying the Framework

In a research project with Norwegian mass customizers, the proposed framework has been applied. The three SMEs are now about 6 months into their development process for configurators. They are organizing their projects in accordance with the process model in Fig. 4. The characteristics of the companies are summarized in Table 3.

Company A is developing a configurator solution for windows and doors. A critical issue for them is to find a configurator solution that can allow for both end users and their dealers to collaborate. Different dealer discounts have been identified as a concern in their further progress. The company reported that the development of personas was a fun and an engaging activity and created a lot of laughter. They often had specific customers in mind when picturing their different persons. Company A found customer journey development to be time-consuming but beneficial in order to generate ideas for new ways to communicate with their customers.

Company B is creating a configurator for kitchen extractor hoods. They also have encountered the need for supporting both private customers and kitchen dealers. Many different types of actors serve as influencers in the decision-making process. The loyalty to long-term dealers as partners is both a challenge and an opportunity for a new product configurator solution. In large projects, it could be architects, building managers, or ventilation companies that affect the final purchasing decision. Still for the end customers, design and customization to specific colors and measures are important. The navigation process must allow for flexibility between product selection (finding the right design of the hood) and product configuration (size, color, functions).

Company C is developing a configurator for waste bins. In addition to being a pure product configurator, the company have identified additional needs for their customers. A tool to help customers understand their real need for waste management is proposed. The company had experience with designing customer journeys from previous developments. This helped them in terms of efficiency within the initial phases. Linkages with new product development opportunities have been identified. There is a potential for smarter products with sensors and intelligence. An example of how company C used personas and customer journeys is given in Fig. 5.

Table 3 Case company characteristics

	Company A	Company B	Company C
Product	Doors and windows	Kitchen extractor hoods	Waste handling and cleaning
Solution space	"Infinite" (only limited by physical size)	Thousands (full NCS/RAL color range)	Thousands (full NCS/RAL color range)
Primary sales channel	Builders' merchant chain stores	Kitchen suppliers	Dealers with purchasers for large-scale projects
Important stakeholders	Carpenters, architects, end customers	Kitchen suppliers, interior architects, end customers	(Interior) architects, building owners (e.g., airports, schools)
Product variety determinants	Glass, insulation, shape, size, crossbars and posts, openings and colors	Model type, material, size, color	Model type, color, waste bin labeling

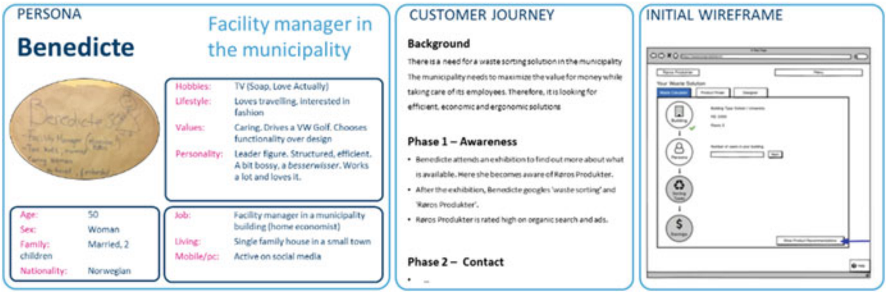

Fig. 5 Example of persona description, customer journey extracts, and wireframe sketches

6 Common Traits and Challenges

Little Direct Contact with the End Customer They all have a strong reliance on dealer networks, which severely influences the customer's exposure to their products. However, this creates a potential for improved dialogue with end customers through a configurator and other online and social platforms. Further, it means that all three companies need to design configurators that allow for different views and information layers, such as pricing information and discount structures.

Complex Choice Process All cases currently have time-consuming order clarification procedures, with many rounds for clarification by e-mail, phone, or store consultation. This is not scalable according to their own growth ambitions. There are many actors involved in the decision-making, and little automation exists today.

Customers Have Other Concerns All three case companies have customer journeys where their customer is preoccupied with bigger decisions. For case A, their customers might need a house, not only a window. For case B, their customers often need a new kitchen, not only an extractor hood. For case C, their customers need a complete recycling management solution, not just waste bins. Then again, all three companies also see that some of their customers is willing to invest a lot in specifying exactly the right product for their need. Private customers spend much time and energy with identifying the perfect window, hood, or bin for their project. This will influence the configurator design in terms of efficiency, choice options, and visualization.

7 Discussion

A Customer-Centric Process Model The? currently identified models for how to address a product configurator process seems to have characteristics that calls for an alternative. The models of Haug et al. [14] and Forza and Salvador [12] can be argued to be linear, expert-driven, and function-based. We have developed a new process model that aims to be cyclic, customer-driven, and need-based. We believe that the inclusion of elements for lean user experience and agile development can help SMEs to swing their focus toward rapid iterations of testing and learning from the customer. However, previous models have merits in offering detailed advice on information modeling, requirement specification, and feasibility analysis. We merely hope to add new elements into what we believe to be critical for SMEs when developing sound choice navigation for demanding customers while still keeping simplicity and flexibility for small enterprises with limited resources.

From Function-Based to Need-Based Configurators It is recommended to guide the customer though a series of easily understandable choices based on his or her needs. Starting out with customer needs instead of product functionality can allow for better choice navigation. As stated in the cross-case analysis, several of the SMEs have customers that have larger project at hand. This is in line with Randall et al., finding that less-expert consumers were significantly more satisfied using need-based interface, compared to a parameter-based interface [26]. As the physical and digital world gets increasingly intertwined, there are strong arguments to be made for basing online navigation and behavior on real-life needs and demands. As they say, “you need a hole, not a drill!” For the choice navigation process, this means that one could broaden the set of touchpoints where the customer can interact with the company.

Provide Value to Multiple Parties All three case companies experience a form of “dealer squeeze.” They rely on their distributors for sales and marketing but then have less influence on the communication with end customers. Configurators can be an opportunity to mitigate this situation. Collaboration can also be done with the essential influencers (architects, interior designers, engineers, ventilation experts, etc.). The SMEs can use their digital platform to offer a unified way of storing product data easily. This can be valuable for their partners, such as 3D visualizations, Building Information Modeling (BIM) objects, and environmental information about the configuration.

Teach Your Customers The three SMEs in this case study report that their domain knowledge and product expertise are key competitive advantage. Designing customer journeys that specify where domain knowledge is needed is an advantage. By contributing with product knowledge in the context of the customer, they enable choices that better suits his or her needs. Further, creating a *positive experience* during the design is vital, particularly toward the consumer market. Experience go hand in hand with learning, and when you are able to teach your customer something useful or surprising (relevant to the product), it can contribute to overall satisfaction.

Learn from Your Customers Establishing modern product configurators allows for a new source of insight about your customers. Analyzing “big data” about how the configurator is used is important for revising the configuration process itself. Configurator usage data can also provide important insight to developing new services and products. What do people spend time on? Which configurations sell well – and why? Where do customers drop out – and why? And do they interact with others during the configuration process? This information can be used to test new features and functions.

8 Conclusion

In this paper, we have developed a new process model for configurator projects that aims to be cyclic, customer-driven, and need-based.

Implication for Managers We propose five ways for managers of SMEs to mitigate the paradox of choice and the anticipated regret:

1. Start simple and measure feedback continuously.
2. Use a flexible configurator system.
3. Ask simple, quantifiable questions.
4. Do not use a linear configuration; previous selections should be transferred to new models.
5. Make small but many improvement cycles.

Implication for Research Current process models from literature are characterized by being linear and focusing on technical aspects of the configurators. They seem to have a strong emphasis on information modeling, requirement specification, and feasibility analysis. A main contribution from this paper is to propose a cyclic process model that aims from more frequent interactions with actual customers along the way. The goal is to develop a choice navigation processes that is founded in the actual needs of the customer instead of different functional aspects of the product. Introducing personas and customer journeys in the process is one way to lead this way toward customer focus.

Future Research We will continue the development of the process model and will have stronger empirical evidence as the Custom^{R} research project progresses. We call for more research that refine and test process models for developing choice navigation in an SME context.

We specifically call for more studies on the integration of product configurators with *back-end systems*. How can this be best achieved, and what effects can be seen from integrating a commercial product configurator with order management systems and systems for production planning and control. Reports on this type of integration with front-end and back-end systems are interesting to learn how to achieve seamless flows of information between the customer and the company.

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User Interface Trends for Mobile-Optimized Product Configurators

Paul Blazek and Klaus Pilsl

Abstract Until now studies and research haven't focused on the importance of mobile-optimized product configurators, but this topic was rather mentioned in articles and blogs. Since millennials, the first truly digital generation of people born between 1980 and 2000, have a rising online purchasing power and prefer mobile phones to desktop devices, this topic is relevant for science dealing with mass customization and configurators. Thirty percent of millennials use their mobile phone for shopping; furthermore they are interested in personalized or customized products. Four in ten millennials are open to co-create products with companies. So it can be assumed that offering customizable products and services optimized for mobile usage may have a significant relevance. This paper will take a closer look at the status quo of online product configurators regarding mobile optimization in the apparel industry. A quantitative and qualitative research will try to find out if there are any user interface design trends to pave the way for further research.

Keywords Millennials · Mobile · Online configurator · User interface design · User interface trends · Customization

1 Introduction

Several articles and studies stress the importance of offering customizable products for the Generation Y, also known as millennials, persons born between 1980 and 2000. They are the first so-called digital natives – grown up with digital technologies and the World Wide Web – highly preferring their mobile device over tablet and desktop devices [1, 2].

This generation longs for individuality and honors to be involved in purchasing processes – and that by using their smartphones [3]. Moreover the households of the

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millennials are growing which implies that also their purchasing power is growing. Fifty-one percent of observed online transactions of consumer packaged goods are made by millennials (US customer analysis) [4].

Companies focusing on millennials as customer group should be aware of the fact that they mainly surf the internet with their smartphones. Due to that reason, they should provide them with mobile-optimized information and services.

As millennials long for individuality and their preferred devices are mobile phones, it can be assumed that mobile-optimized product configurators seem crucial to be accepted and used by this generation.

Regarding to a study in 2012, 40% of the millennials are open to co-create products [5]. Furthermore in 2016 a project found out that already 50% of this target group have purchased a customized product online [6]. But no research concerning the usage of mobile-optimized configurators and millennials was found.

The following study shall give a first insight into the status quo of mobile-optimized configurators. Furthermore it covers a quantitative and qualitative analysis of mobile-optimized configurators of the apparel industry according to user interface trends and may be a fundament for further research with millennials.

2 Relevance of Mobile Optimization for Configurators

2.1 Status Quo of Mobile Usage in General

In November 2016 the independent web analytics company StatCounter reports that Internet usage by mobile and tablet (51.3%) devices exceeded desktop (48.7%) usage worldwide for the first time. This statistics are based on over 15 billion page views per month to over 2.5 million websites [7]. Also the annual report of Internet Trends 2017 by Mary Meeker shows a constant rise of time spent per adult per day with digital media (Internet usage) in the USA. Mobile usage counting 3.2 h per day is exceeding desktop usage with 2.2 h per day [8].

In 2016 Google published a report conducted with 11,964 cross-device Google users in the USA between 18 and 49 years, emphasizing the topic “How People Use Their Devices.” The key findings are that people live in a mobile-first world as on an average day one fourth of all probands (27%) only use a smartphone; nevertheless over half of the users rely on more than just one type of device every day. Overall 80% of the probands use a smartphone, 67% use a computer, and only 16% use a tablet. Another finding is that nearly four in ten users search only on smartphones – so search has gone mobile too [9]. In this context, Google also announced that it will favor mobile-friendly websites in their ranking on mobile searches compared to websites which are not optimized [10].

When taking a closer look at the demographics of US smartphone owners, the highest penetration concerning age is among millennials aged 18–24 years with 98%, followed by millennials aged 25–34 years with a 97% ownership rate.

Nevertheless 96% of 35–44 aged – called Generation X – own a smartphone [2]. Also Facebook data revealed that in the holiday season of 2015 Millennials, Moms and Multicultural shoppers in the USA collectively did 81% of all mobile transactions. Thirty percent of online purchases by millennials are made on mobile devices, and 62% state that they use their mobile phones for shopping because they can do it anytime and anywhere. Millennials use nine times more likely their mobile phone over their tablet when shopping than people of the age 55+ [11].

2.2 Millennials as Potential Customer Group

Millennials are seen as the first digital natives, who have become the largest generation in the American workforce in 2015. Digital native is a person who is raised in a digital, media-saturated world. Although the defined range millennials are born in diversity, the most generally accepted range is 1980–2000 [1]. Many studies and articles concerning habits and characteristics of millennials as crucial consumer and workforce can be found online. Some of them are listed in the following.

Millennials are said to be slower in terms of getting married and moving out on their own than other generations. Furthermore they prefer spending their time and money on exercising and healthy food [12]. Nevertheless they would rather buy a car and rent a house than the other way around [13].

Smartphones are a dominant device for millennials to connect to the web [14]. Growing up in a digital world gives them instant access to price comparisons, product information, and peer reviews [12]. When millennials need shopping information, they use social media as their primary source to look for and hear about products, special deals, and shopping news [14]. Millennials aren’t influenced by advertising to trust a brand more. For making purchasing decisions, they rely on blogs, social media, and their peer group [13]. As millennials are said to be price sensitive, they use Amazon and Google to compare prices [14].

Millennials value authenticity over content in terms of consuming news, which means that they only trust the content of companies and news sites they know. If brands engage with them on social networks, they are more likely to become loyal customers. However they stay brand loyal if they have built a relationship to a company. It’s important to them that brands give back to society than just making profit, and they favor companies that support their local communities [13].

A study by Nielsen Norman Group focuses on a subgroup of millennials, in the age between 18 and 25, namely, today’s young adults. They are seen as an important user group, as they start to earn money and are comfortable in spending it online. The study – taken in seven countries – explored how far the internet usage of young adults differs from teenagers and older adults (35 years or older). They discovered that young adults like interactivity only when it serves a purpose and not for enjoyment, in contrast to teenagers. They are sensitive to the tone of a website. They don’t like if they have the feeling the site is talking down to them or trying too hard to appear cool. They are very skeptical of information presented on websites and demand more evidence to support claims than teenagers do. When comparing with older adults, they tend to be extremely confident in their own ability to navigate digital interfaces and going through new design patterns. They have a different visual appeal on websites than older users. The results of the study underline the importance of testing interfaces with representative user groups [15].

2.3 Relevance and Experience of Online Customization by Millennials

More than any other generation, millennials demand to be seen as unique within a group. They want services and products that fit exactly to their individuality. They also reject brands in favor of their own personal clothing style. So millennials seem to prefer brands that offer customization possibilities. Because of that companies started to allow their customers to customize products from ground, for example, Shoes of Prey offers customizable shoes for women, and Nike offers its customers individual running shoes [3]. For that reason millennials have been nicknamed “Generation DIY” [16].

Already in 2012 a study with 4000 millennials found out that 4 in 10 millennials are open to co-create products with companies [5]. However, a quantitative empirical research conducted in 2016 with 247 members of the Generation Y states that only 50% of the participants have customized and purchased a product already. The top three reasons for customizing products are “The product meets my aesthetic taste,” “It’s fun being creative by ‘Doing Yourself’,” and “The product has the form/function I need.” The mainly stated factors for not having customized a product yet are “It’s too expensive,” “The configuration process is too laborious,” and “I miss the shopping experience when shopping online.” Companies are equally evaluated by millennials whether or not they offer customizable products. Companies offering mass customization are however better rated in terms of customer orientation, topicality, and professionalism. Furthermore this research claims that the target group has already made customization experiences with the following products [6]:

- Personalized media, e.g., photobooks (42%)
- Casual fashion, e.g., T-shirts (30%)
- Personalized products, e.g., bag and mugs (12%)

Facebook published a study about the behavior and attitudes of mobile-first car consumers in the USA compared to the desktop-first car consumers. One of the outputs is that 71% of the participants use their mobile phones during the car purchasing process. Nevertheless one of the friction points is that when it comes to customization and comparison tools, 58% complain that they have to switch to desktop as it works best there [17]. Changing devices while customization is not very user friendly and a bit backward. Instead user interfaces of configurators for mobile usage should be optimized and designed much simpler. It is crucial to make configurators mobile accessible for millennials; otherwise companies may resign sales from the mobile-first generation [18].

2.4 Importance of Mobile Customization by Millennials

Due to the research concerning the mobile usage of millennials, it can be supposed that millennials would also like to configure their favorite products via smartphone. One of the outputs of a study in 2016 was that millennials criticize the handling of product configurators and demand improvement. It is assumed that there may be weaknesses in the usability, access, handling, and freedom of creation [6].

Therefore the present study will take a closer look at the status quo of mobile-optimized product configurators in diverse industries and will focus on an industry which is relevant for millennials.

3 Empirical Analysis

3.1 Research Aims

Several analyses emphasize that millennials are the biggest generation of mobile-first users. As well some research shows that this generation is willing to customize products online. Therefore it seems crucial to analyze the availability and status quo of mobile-optimized solutions of product configurators, if serving this special target group.

The main aim of the following study is to gain insight into the status quo of mobile-optimized configurators; so the research questions focus on the following two key aspects:

- Are there existing mobile trends according to special predefined criteria?
- Is it possible to group mobile configurators regarding their user interface design and structure?

To answer the first research question, the configurators were analyzed in a quantitative study according to special criteria defined together with experts that work on the configurator database (www.configurator-database.com).

Afterward in a qualitative analysis, user interfaces of mobile-optimized configurators are compared and clustered.

It is assumed that user interface designs may vary according to a certain industry; therefore this study focuses on one industry. The analyzed industry is derived by having a closer look at the status quo of device-optimized configurators listed in the Configurator Database Report 2016 [19], which is described in detail in Sect. 3.2.

The gathered output of the following study shall help to get a first idea of the usage and structure of mobile configurators and set a foundation for further research.

3.2 Status Quo of Online Product Configurators Regarding Mobile Optimization

The Configurator Database Report 2016 [19], covering 1200 international web-based product configurators, states that almost 20% ($n = 218$) of the analyzed configurators are adapting to different user devices. All 1200 configurators have been categorized in 17 categories. Figure 1 depicts an industry ranking of the configurator database in total and shows the amount of device-optimized configurators in each industry. When considering the percentage of each industry, *footwear* with 40% (16 out of 40), *pet supplies* with 38.89% (7 out of 18), and *sportswear and equipment* with 25.51% (25 out of 98) are leading.

When taking a closer look at the device-optimized configurators, Fig. 2 shows that the *apparel* industry is leading by covering almost 18% (total 39) of all device-optimized product configurators, followed by *house and garden* with 14.2% (total 31), and *sportswear and equipment* with 11.5% (total 25) [19].

Nevertheless 80% of the 1200 configurators still offer only a desktop resolution; so there may be a high potential in terms of tablet and mobile optimization.

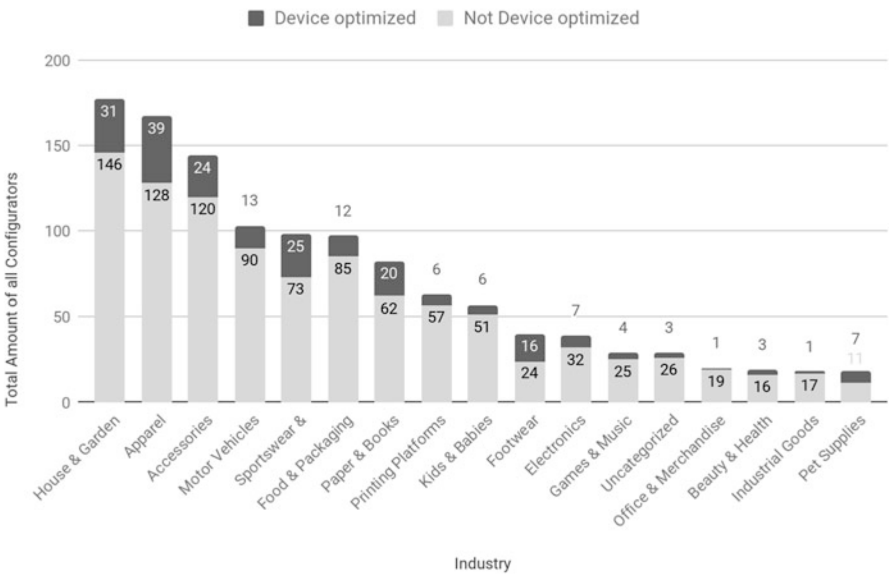

Fig. 1 Industry ranking of configurators ($n = 1200$): amount of device-optimized configurators vs. not device-optimized configurators

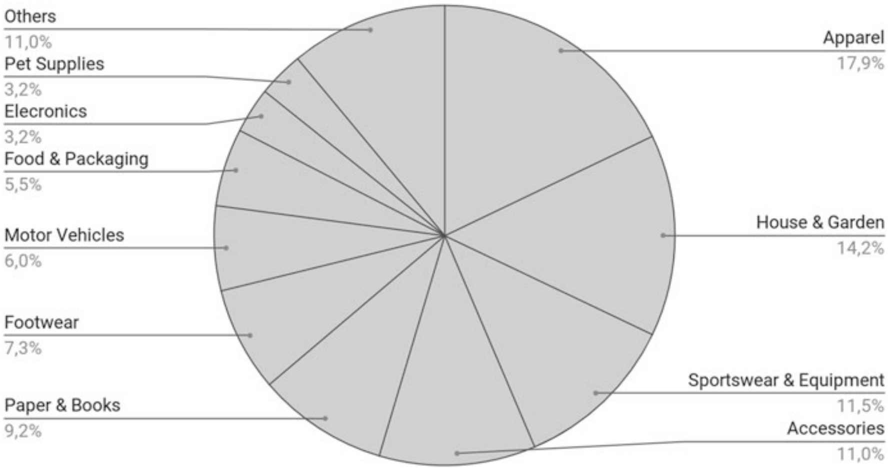

Fig. 2 Device-optimized configurators ($n = 218$)

Defining the Industry The empirical analysis of this study focuses on only one industry. To strive for the right industry, the Configurator Database Report 2016 [19] and a study of Junker et al. [6] are considered.

As shown in Fig. 2 from all 218 device-optimized configurators of the Configurator Database Report 2016, the apparel industry offers with the amount of 39 most of all responsive configurators. That are 23.5% of all 167 configurators in the apparel industry covered in the Configurator Database Report 2016 [19].

As mentioned before, when taking a closer look at customizable products, millennials have experience with personalized media, e.g., photobooks (42%); casual fashion, e.g., T-shirts (30%); and personalized products, e.g., bag and mugs (12%) are the most favored products for customization [6].

As the largest sample of mobile configurators can be found in the apparel industry [19] and customizing *casual fashion* is the second largest product category, millennials have experience with [6]; this study will concentrate on the apparel industry.

3.3 *Method and Setting*

In the following the method and setting are described to find possible analogies of mobile-optimized configurators within the apparel industry according to predefined criteria (see Sect. 4.1) and to gather possible trends according to the user interface design and structure of these configurators (see Sect. 4.2).

The study was conducted in June 2017, so if any configurator of the sample has been modified afterward, it is not considered in the study. The configurators were accessed and screenshotted with an Android smartphone.

Quantitative Data Evaluation to Detect Mobile Analogies Within the Apparel Industry All mobile-optimized configurators are quantitatively evaluated for this study with the following criteria that have been developed together with experts that work on the configurator database (www.configurator-database.com):

- Product Categories: Which product categories are offered in the apparel industry?
- Amount of Customization Options: How many customization options does a configurator provide?
- Flexibility of Configuration: Which configurators provide a flexible or a process navigation?
- Alignment of Navigation: Is the navigation vertically or horizontally aligned?
- Icon Usage for Navigation: How many configurators use icons for the navigation? Do they use icons solely or in combination with text?
- Product Visualization: How many configurators depict a product image? Is the product image live-updated? How many views of a product image are provided?
- Scrolling of the Screen: Is it necessary to scroll within the configuration process?

Qualitative Approach to Identify User Interface Design and Structure Trends The procedure to identify possible trends concerning mobile-optimized configurators in one industry is the following:

1. The sample of mobile-optimized configurators within one industry is taken from the Configurator Database Report 2016 (Appendix Table 1).
2. Each configurator is screenshotted with a mobile device in detail.
3. Based on the screenshots, all configurators are compared and clustered concerning their appearance of user interface design and handling.
4. The output is whether or not the configurators can be classified in specific clusters.

4 Results and Key Findings

4.1 Quantitative Data Evaluation Within the Apparel Industry

The first intent of this quantitative study is to figure out whether or not all of the 39 device-optimized configurators of the apparel industry are fully accessible on mobile phones. The difference between device-optimized and mobile-optimized means that device-optimized configurators may behave responsive on desktops, tablets, and mobile; nevertheless in some cases, they are only optimized for tablets and not for mobile usage. So mobile-optimized configurators are adjusted for smartphone usage.

In a second step, only the mobile-optimized configurators are analyzed according to predefined criteria to detect certain trends. A detailed description of these criteria can be found in Sect. 3.2. For the data evaluation, an Android smartphone was used to guarantee a mobile insight. In the following the results of the quantitative study are summed up.

Research Results The research shows that when accessing all 39 device-optimized configurators of the apparel industry on a smartphone, only 33 are mobile-optimized. Therefore the quantitative analysis according to the predefined criteria is conducted with 33 configurators, providing the following results:

- *Product Categories*: The leading product categories are shirts ($n = 11$) and T-shirts ($n = 10$) followed by suits and sweatshirts, both counting three configurators. Jackets are provided by two companies. Jeans, dirndl, and hoodie customization is offered only once (Fig. 3).
- *Amount of Customization Options*: 8 out of 33 configurators offer 5 customization options, followed by 4 customization options ($n = 5$), and 7 customization options ($n = 4$). The highest amount of customization options is 36, offered by one suit configurator (Fig. 4).
- *Flexibility of Configuration*: 24 configurators provide a flexible navigation; only 8 configurators provide a process navigation. One configurator allows a flexible and a process navigation. Flexible navigation means that a user is free to pick the favored customization option, whereas process navigation means that the system provides the user with the customization option.

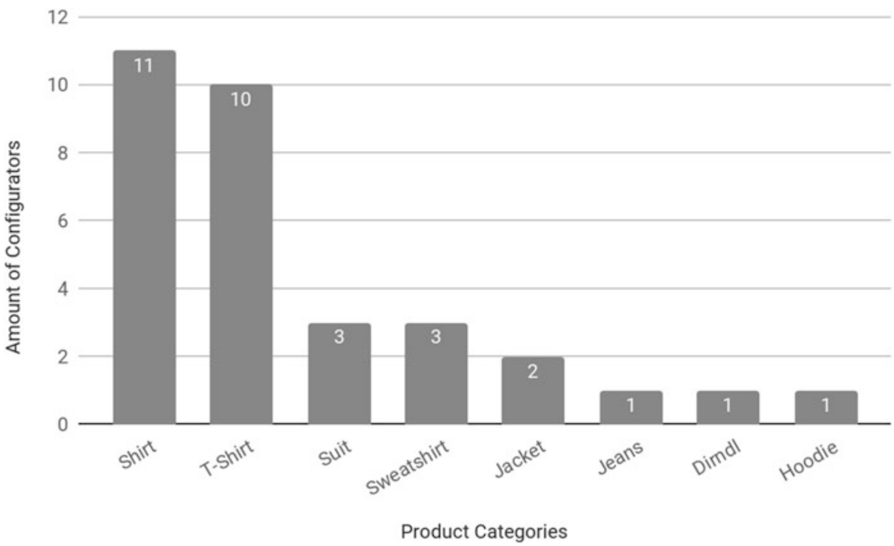

Fig. 3 Product categories of mobile-optimized configurators

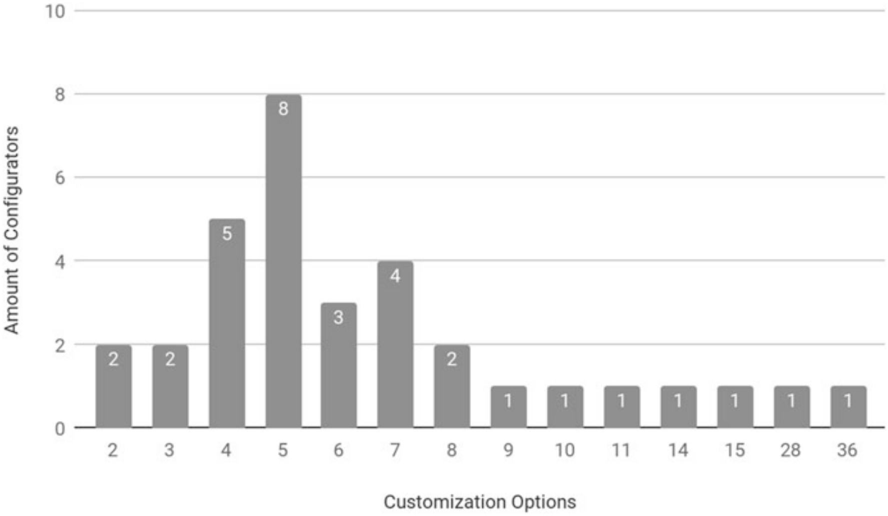

Fig. 4 Amount of customization option ($n = 33$)

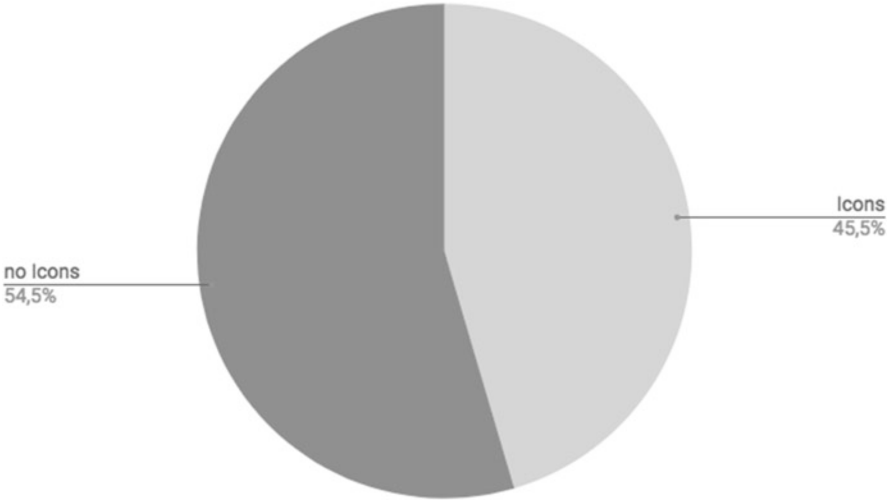

Fig. 5 Icon usage for navigation ($n = 33$)

- *Alignment of Navigation*: 20 configurators have a vertical navigation, 11 have a horizontal navigation, and 2 use both.
- *Icon Usage for Navigation*: 45.5% ($n = 15$) use icons for the navigation, whereas 5 use no further text and rely just on the significance of the icon (Fig. 5).

- *Product Visualization*: 25 of the 33 configurators depict the product visualization, and almost all of them are live-updated when a customization option is chosen. Fourteen of the 25 visualizations offer more than one view of the product, and 23 show the product in a 3D look.
- *Scrolling on the Screen*: 21 configurators have to be scrolled by users to customize a product, whereas 12 configurators allow to customize a product on one screen without scrolling. Nevertheless 6 of these 12 configurators have in some extent configuration options, which have to be scrolled, when selected.

4.2 Qualitative Data Evaluation Classification of User Interface Design

The 33 mobile-optimized configurators of the apparel industry were screenshotted and analyzed according to their user interface similarities. The classification process results in four user interface design approaches:

1. Collapsible approach
2. Visualization-centered approach
3. Step-by-step approach
4. Outliers – not fitting to any approach

The visualization-centered approach is most popular with covering 12 configurators, followed by the collapsible approach with 11 as seen in Fig. 6.

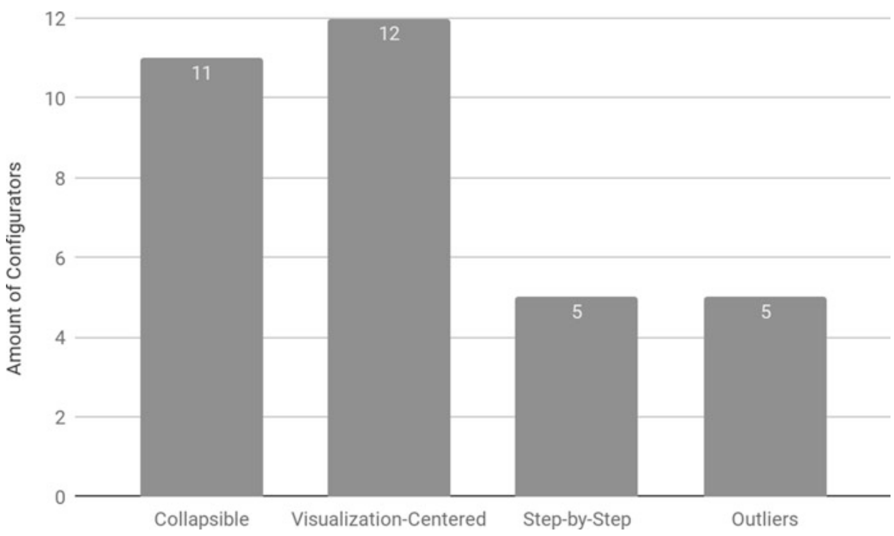

Fig. 6 User interface clustering ($n = 33$)

In the following each approach is described in detail and illustrated with examples:

1. *Collapsible Approach*: In this approach customization options of a product are represented as a toggle or accordion navigation. Toggle navigation in this context means that the various customization options can be opened and closed independently, whereas an accordion navigation allows that only one customization option can be opened at the same time. The visualization of the product – if existing – is above or below the toggle or accordion navigation or hidden behind a button. In most of the cases, the screen has to be scrolled.

   Example 1: DesignYourDirndl (Dirndl)

   DesignYourDirndl offers the customization options in a toggle navigation and shows a live-updating product visualization below the toggle navigation. The user has to scroll to see the configured product (http://www.designyourdirndl.at/produkt-kategorie/build-your-own/).

   Example 2: The North Face (Outdoor Fashion)

   The North Face configurator depicts a live-updating product visualization at the very top. Underneath the customization options are presented as accordion navigation (https://www.thenorthface.com/custom-products/custom-denali.html).

   Example 3: ShirtbyHand (Shirts)

   ShirtbyHand covers the customization options in an accordion navigation. On the right side of the screen, a small thumb image of the product is depicted. As it is affixed to this position, it is always present while scrolling. The live-updating product visualization opens as an overlay via click on the thumb image (http://www.shirtbyhand.nl/).

   Example 4: Indochino (Suits)

   Indochino uses no product visualizations, only thumbs to visualize configuration options. These options are presented in a toggle navigation (http://www.indochino.com/).

2. *Visualization-Centered Approach*: In this approach the product visualization is depicted in the center of the screen, and the customization options – clustered and presented as toolbox – are aligned on the top, bottom, left, or right of the visualization. In most of the cases, the screen is fixed, and the user doesn't have to scroll.

   Example 1: UglyChristmasSweater.com (Sweatshirt)

   UglyChristmasSweater.com aligns its customization options at the top, above the product visualization. The visualization is live-updated (http://www.uglychristmassweater.com/customizer/).

   Example 2: Shirttuning (T-Shirt)

   Shirttuning hides the customization options behind a button on the left side of the screen. Via click all options appear as an overlay. The product is live-updated and offered in four views (https://www.shirttuning.de/t-shirt-selbst-gestalten.html).

Example 3: Shirtinator (T-Shirt)

Shirtinator offers the customization options on the right side of the screen, opening via overlay. Via click on an option, a toolbox fades in. The product visualization is offered in four views (http://www.shirtinator.de/creator_de/).

Example 4: Tailor Store (Shirt)

Tailor Store aligns the customization options on the bottom of the screen, presenting the choices fullscreen. The visualization is live-updated (http://www.tailorstore.com/us/en/tailor-made-shirts).

3. *Step-by-Step Approach*: In this approach the user is guided through the configuration process. The product visualization (if existing) is in all cases above the steps.

   Example 1: Dragon Inside (Suit)

   Dragon Inside presents its step-by-step navigation at the very top, leading the customer through the process. The customization options are visualized as small thumbs. Each step covers one customization option. There is no visualization of the whole configured product
   (http://www.dragoninside.com).

   Example 2: Proper Cloth (Shirt)

   Proper Cloth fixates its step-by-step navigation at the very bottom. A step covers more than just one customization option. Each customization option opens in a new screen (http://www.propercloth.com/custom-dress-shirts/).

   Example 3: Smart Jeans (Jeans)

   Smart Jeans depicts a live-updating product image at the very top. When scrolling to the very bottom, the step-by-step navigation appears. The customization options are in between the visualization and the forward and back button (http://www.smart-jeans.com/).

4. *Outliers*: 5 of the configurators have a different way of handling the customization process and can't be added to one of the other classifications.

4.3 Premise of the Analysis

The analysis focuses on the apparel industry, which gives only a narrow insight into the high variety of configurators. The quantitative results give a good overview of the status quo of mobile-optimized apparel configurators; nevertheless it doesn't tell which approach is valued by customers or affects their purchasing behavior. So it is recommended to test these outputs in a qualitative user testing. However the study gives a first orientation for further research. Configuration apps are excluded from this study but may be an interesting field of research concerning millennials, as they are said to be heavy app users.

5 Conclusion and Outlook

Millennials are the first generation which favor mobile to desktop devices and have a growing online purchasing power. Furthermore they want to be included in product co-creation processes and appreciate individuality. Therefore the question of the relevance of mobile-optimized configurators emerges. Currently no studies concerning mobile configurators were found, so this research gives a first convergence to this topic.

The results of this study show that almost 20% of all configurators within the database ($n = 1200$) are responsive. The industries with the highest percentage of responsive configurators are *footwear* with 40% (16 out of 40), *pet supplies* with 38.89% (7 out of 18), and *sportswear and equipment* with 25.51% (25 out of 98). If considering only the device-optimized configurators ($n = 218$) of the Configurator Database, the *apparel* industry is leading with 18% ($n = 39$), followed by *house and garden* with 14.2% ($n = 31$), and *sportswear and equipment* with 11.5% ($n = 25$). Looking at the apparel industry, which is relevant for millennials, the mobile configurators can be grouped in four different user interface types: the collapsible approach, the visualization-centered approach, the step-by-step approach, and the outliers. The visualization-centered and the collapsible approach are used most. In general 25 of the 33 configurators depict a product visualization, and almost all of them are live-updated when a customization option is chosen. One third of the configurators offer four or five customization options, and two third have a vertical navigation.

The user interface design approaches in the apparel industry should be tested with millennials to figure out whether or not these approaches are worth to keep track of. With the help of a flexible configurator management system (www.combeenation.com), different user interface types can be tested in a simple and efficient way and lead to insights on how the best satisfaction of needs and value creation for millennials can be achieved.

Appendix

Table 1 Sample of 33 apparel configurators [19]

No.	Company name	URL	Product
1	DesignYourDirndl	http://www.designyourdirndl.at/produkt-kategorie/build-your-own/	Dirndl
2	Inkmar	http://www.inkmar.com/customdesign	Hoodie
3	Clothoo	http://clothoo.com/design-custom-varsity-jacket/	Jacket
4	The North Face	https://www.thenorthface.com/custom-products/custom-denali.html	Jacket
5	Smart Jeans	http://www.smart-jeans.com/	Jeans
6	hemdwerk	https://www.hemdwerk.com/konfigurator	Shirt
7	Herren Globus	https://www.herrenglobus.ch/design-your-shirt/shirtkonfigurator	Shirt
8	Marks and Spencer	http://www.marksandspencer-madetomeasure.com	Shirt
9	Masshemd	https://www.masshemd.com/konfigurator/shirt	Shirt
10	Modern Tailor	http://www.moderntailor.com/	Shirt
11	My Tailor.com	http://www.mytailor.com/	Shirt
12	Proper Cloth	http://www.propercloth.com/custom-dress-shirts/	Shirt
13	ShirtbyHand	http://www.shirtbyhand.nl/	Shirt
14	Suitsupply	http://eu.suitsupply.com/de/product-custom?tid=shirtconfigurator	Shirt
15	Tailor Store	http://www.tailorstore.com/us/en/tailor-made-shirts	Shirt
16	Sumissura	http://www.sumissura.com	Skirt/shirt
17	Dragon Inside	http://www.dragoninside.com	Suit

(continued)

Table 1 (continued)

No.	Company name	URL	Product
18	Indochino	http://www.indochino.com/	Suit
19	My.Suit	http://www.mysuit.com/website/Separates/SeparateBuilder.aspx?pgName=S	Suit
20	Bow & Drape	http://www.bowanddrape.com	Sweatshirt
21	JazzyShirt	https://www.jazzyshirt.de/t-shirt-selbst-gestalten.html	Sweatshirt
22	UglyChristmasSweater.com	http://www.uglychristmassweater.com/customizer/	Sweatshirt
23	Just Jen	http://www.justjen.com/shop/custom-tshirts.htm	T-shirt
24	koordinatenshirt	http://www.koordinatenshirt.com/	T-shirt
25	Saltycustoms	http://www.saltycustoms.com	T-shirt
26	Shirtcity	http://www.shirtcity.us/t-shirt-create	T-shirt
27	Shirtinator	http://www.shirtinator.de/creator_de/	T-shirt
28	ShirtMagic	http://www.shirtmagic.com/	T-shirt
29	Shirttuning	https://www.shirttuning.de/t-shirt-selbst-gestalten.html	T-shirt
30	Son of a tailor	https://www.sonofatailor.com/designer	T-shirt
31	Spreadshirt	http://www.spreadshirt.com/design-your-own-t-shirt-C59	T-shirt
32	Tee Junction	http://www.teejunction.com.au/create	T-shirt
33	Tostadora	http://www.tostadora.co.uk/personalised-t-shirts.php	T-shirt

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An Evaluation Model for Web-based 3D Mass Customization Toolkit Design

Huiwen Zhao, Leigh McLoughlin, Valery Adzhiev, and Alexander Pasko

Abstract The development of geometric modelling technologies and web technologies provides the ability to present a virtual 3D product in a mass customization (MC) toolkit. Compared with 2D graphic toolkits, 3D toolkit design requires better consideration of individual customer needs, consumer and toolkit interaction, and also a means of integrating with the underlying technical infrastructure. However, there is currently no widely accepted model or criteria to regulate and evaluate 3D MC toolkit design. Given these considerations, in this paper we provide an evaluation model for web-based 3D toolkits and a heuristic evaluation of two representative commercial web-based 3D toolkits. The evaluation results indicate the usefulness and effectiveness of the model as a scale for evaluating 3D toolkits. It also reveals that despite a fair amount of effort that has been devoted to theoretical research, current 3D toolkits are still at an early development stage. We therefore conclude this paper by identifying and encouraging further topics and questions as directions for future research.

Keywords Mass customization toolkit · 3D toolkit design · Evaluation model · Interaction design · 3D modelling · Heuristic evaluation

1 Introduction

The key significance of mass customization (MC) is to provide personalized service and products to meet each consumer's needs and desires [7, 29, 37]. To achieve this, consumers are allowed to take part in activities and processes which used to

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be controlled by the companies [47]. Toolkits therefore have been widely used in industry as a medium between consumers and manufacturers. Since powerful computers, high-speed Internet and sophisticated web browsers facilitate the efficiency of developing customized products, most toolkits nowadays are computer-based and especially web-based. They allow consumers to design their own products or service by trial-and-error experimentation and also deliver immediate feedback of the potential outcome of their design ideas [17, 29, 34].

More importantly, the development of geometric modelling provides the means of presenting a virtual 3D product in a mass customization toolkit. Compared with 2D graphic toolkits, 3D toolkits stimulate a 3D product environment that can be interacted with in a seemingly real or physical approach. Therefore, 3D toolkits provide a more direct interaction experience. Consumers can zoom in/out and rotate 3D models to envision the final products [7, 26]. Instead of clicking buttons or moving sliders to customize the product, in certain systems consumers can even directly manipulate 3D models, which gives them a better sense of control. Daugherty et al. [6] claimed that consumers' experience in a 3D environment is similar to examining the real product in a shop. Other researchers [26, 30, 31, 46] agreed that 3D toolkits create a more satisfying experience for consumers than 2D graphic toolkits, which then helps to increase the propensity of purchase. Therefore, 3D toolkits have been considered as the trend of design communication between consumers and manufacturers [22].

However, the adoption of 3D MC toolkits is still at an early stage. Compared with 2D graphic toolkits, 3D toolkit design requires "greater understanding of customer needs, design options and 3D image representation" [26]. A number of studies showed that poor 3D visualization leads to a higher chance of disorientation or motion sickness [30, 31, 46]. In addition, consumers may have difficulties in understanding 3D virtual models [15]. To achieve effective mass customization, it is therefore vitally important that the 3D toolkits are designed to elicit a satisfying consumer experience.

Given these considerations, this paper aims at designing an evaluation model to assess 3D MC toolkits. In working towards this goal, a literature review is presented in the following section, covering different aspects of 3D toolkit design. Based on the literature review, an evaluation model is proposed, and two 3D MC toolkits are evaluated using this model. In conclusion, significant research findings are presented, and new research questions are identified.

2 Literature Review

The primary task of a mass customization toolkit is to help consumers as they design or modify a product or service to meet their needs and requirements. To achieve that, it is important to offer consumers appropriate customization options. Solution space, which is understood as all the possible designs a toolkit can provide, has been considered as a determinant factor for designing an effective toolkit [15, 17].

2.1 Solution Space

Solution space decides the design freedom that a toolkit can offer to a consumer. Typically there are two elements related to the design of the solution space: the type of options it provides and the size of the choice set.

Type of Options The type of options is largely determined by the way that a product can be customized. Hermans [15] categorized four different mechanisms for customization: veneer, modularity, parametric and generative. Veneer customization allows consumers to customize products by adding a visual decorative layer to a product. This has been considered as the most common method of offering customization. The possible options for this mechanism include a list of different texts, graphics, patterns or colours which can be added to the surface of the product by processes such as printing, engraving, etching or embroidery. Modularity customization decomposes products into a set of discrete modules and options for their assembly into a customized design are presented to the user. The individual options in this approach usually feature different component designs or functions. Parametric customization is widely used in 3D toolkits, which allows consumers to customize a product by changing specific parametric values which then change the nature of the product in some way. Generative customization creates 2D or 3D forms based on an algorithm or computer programming. For example, consumers can sketch the side view of a chair and extrude it into a 3D model.

In addition to offering different types of options by considering the method of customization, a number of researchers focused on the functional and aesthetic options offered by MC systems and found functional choices require less spontaneous elaboration than aesthetic choices and aesthetic choices tend to be easier to imagine and to elaborate than functional choices [38]. They suggest providing consumers with aesthetic choices should be the main approach to mass customization, because consumers enjoy themselves more when they customize aesthetic features than functional features, regardless of individual ability differences.

Size of Solution Space The size of the solution space is the range of unique final products that a toolkit can produce. It is determined by two factors: the number of attributes for customization and the variety of values given by each attribute. However, the ideal size of the solution space is still a matter of debate. On one hand, results of empirical studies have shown that consumers are actually disappointed by the limited choices offered by most existing toolkits [26]. The majority of consumers would like to have more and a larger variety of choices and also play a more active role in the design of products [11, 12, 27]. On the other hand though, it has been found that consumers can be overwhelmed by the number of choices provided by manufacturers, which may lead to "mass confusion" [10, 28, 43]. Hunt et al. [20] found that the relationship between consumer satisfaction and the number of choices can be demonstrated in an inverted U-shaped fashion, i.e. after reaching a certain point, the more choices provided, the less satisfied consumers are. Another proposed approach to this problem is to convert the number of choices into the number of products in a bricks-and-mortar store to get an adequate understanding of how many choices the customer has [10].

2.2 Interaction Design

For online customization, the process of customizing a product is fundamentally a process of human-computer interaction. The quality of the interaction is crucial for the success of mass customization as it determines whether or not the consumer will be able to complete the customization task [41].

Gerber and Martin [14] suggest that the customization task should be set up step by step as a series of smaller tasks with increasing challenge which helps consumers to avoid getting bored or getting confused. Meanwhile, multiple pathways should be provided to allow consumers to choose their own progression, which helps to give them feelings of autonomy, ownership and control over their creation process [45]. This suggestion has been echoed by [26] which agreed that products which require consumer creativity should be customized in a flexible design procedure. However, for products that require more functionality customization, a top-down hierarchical approach should be used where general features of product functionality are selected prior to detailed design features [25]. Regardless of which approach a toolkit design follows, von Hippel [42] suggests that providing consumers with enough information about the design procedure to let them know which step they are currently in and how many steps there are until completion is very necessary.

In addition, a usable toolkit should provide consumers with clear and proper guidance through all stages of the customization process. For example, a "how-to" video tutorial, a help menu and clickable paths to further explanations can be used as support resources for consumer [14]. In order to encourage creativity, libraries of standard modules should be provided to consumers to help them focus on those aspects of their design that are truly novel, and also a preset design at the starting point is useful to make the process more accessible for consumers [16, 17, 34].

As the Internet has prompted a "participatory culture", the collaboration between consumers helps to foster joint creativity and problem-solving as well as reduce the perception of risk [34]. Therefore, it is useful to provide an online community, such as a chat room, for instant communication, and space for consumers to leave comments or to assess contributions from each other [14, 34]. In addition, a historical record of work and progress of consumer collaboration around a shared interest helps to guide and inspire further product developments [14].

3D toolkits are more effective and satisfying than 2D toolkits to some extent because 3D toolkits allow consumers to directly manipulate on the virtual model of the products [26, 30, 31]. Direct manipulation includes the application of real-world metaphors to make the interaction easier for consumers to learn. In addition, the rapid feedback allows consumers to see the results of their actions, therefore giving them a sense of control and strengthening their beliefs about their ability to take further interactions [2].

2.3 Enabling Technologies: 3D Modelling and Web Technologies

Toolkit design is closely related to technology development. Specifically, 3D modelling and web technologies are the two key enabling technologies for 3D toolkit design and consumer interaction. A variety of 3D modelling technologies and web technologies has been developed, and capabilities of different technologies ultimately dictate what is possible in terms of both the solution space and also the interaction techniques that are available. It is therefore important to consider this layer in order to fully evaluate the capabilities of the MC system.

3D Modelling Technologies The 3D modelling technologies are those which describe the physical shape of the product [18]. This is a virtual representation that is originally defined by the product designer and must be adjustable by the consumer through the interaction design method. 3D modelling technologies are often known as "shape modelling" in the area of computer graphics, which has been used as a generic term for geometric modelling embracing various approaches to representing 3D products. At present, the discipline of shape modelling is in transition from an established design paradigm to a new one, and this is driven by the fundamental requirements that MC rely upon.

The main principle of MC is that the user changes a product through an interactive process. In a 3D MC approach, as the user interacts with the system, the actual shape of the product changes in some way. For this to be possible, the modelling technology has to define not just a single shape but a whole family of shapes. The ways in which the shape is changed from one to another define the interaction design possibilities, and the range of valid shapes defines the solution space.

The method of using adjustable values within a geometric model to change its shape is known as parameterization and is essential in interactive modelling based on user-modifiable definitions [39] and in optimizing shapes to satisfy some design criteria [5]. Mathematical, algorithmic, and software support for defining a parametric family of shapes, such that each new set of parameter values corresponds to another valid instance of a shape, is one of the ultimate goals of shape modelling research and development. It is this parameterization of the model that makes full 3D MC possible, and different methods of parameterization offer different interaction types and different solution spaces. Further, a professional designer and a non-professional consumer have to deal with the same parameterized model using different levels of access to it. For example, a professional designer can decide which parameters consumers can customize, while consumers can only interact with the parameters that the designer selects.

Enabling Web Technologies For the purpose of web-based MC, the consumer needs to interface with the 3D model, to view it and customize the product. Full CAD software is not available or suitable for this application, so lighter weight solutions are needed that run from a web browser. The basic tools available within a web-based environment are HTML and JavaScript scripting language [40]. Some special purpose functionality can be achieved through implementing a small application called an applet which is sent together with the web page to the user and can typically be implemented in the Java language [3]. To handle full interactive 3D graphics, the toolkit needs to employ HTML5 and WebGL [33].

These technologies will allow the user to interact with a local representation, where the 3D object and means of interaction are based in their web browser. In some cases there can be a high computational requirement, especially when modifying the model using a more powerful representation scheme. In such cases it is likely that the local machine, which could be a portable device such as a smartphone or tablet, is insufficient to handle the requests. Here, some or all computations may be handled by a server that the website contacts in the background to perform the heavier computations [1].

2.4 Individual Differences

Toolkit design is a complex topic that is primarily concerned with creating a satisfying consumer experience. However, every consumer is individual and unique, each with their own skills, aesthetic tastes and physical requirements. In order to create a toolkit that satisfies each consumer, the design of a toolkit must account for these individual differences [8, 13, 29, 38].

[9] found that customers who have strong insights into their own preferences and who know what they want tend to enjoy the process more than customers who lack this preference insight. Lin et al. [21] proposed three variables which are associated with individual differences and consumers' perceived value of mass customized products, namely, a need for optimization, a need for uniqueness and centrality of visual product aesthetics. They found that consumers with a higher need for optimization, a higher need for uniqueness and a higher proclivity towards aesthetics tended to be more satisfied with the final product.

In addition, toolkit design should be concerned with individual differences in knowledge, skills, creative talent and even previous experience in mass customization [4, 8, 13, 29, 38]. For consumers who are highly knowledgeable about customizing products, a complex toolkit that provides them with a large number of options is better suited. Similarly, consumers with more Internet experience prefer more substantive features in a toolkit to those with less experience [4]. In comparison, for less experienced consumers, more guides through the configuration process are necessary, and the size of the solution space should be limited to a few customization possibilities. Salvador et al. [36] claimed that consumers who have greater expertise in a product domain are better served by a parameter-based interface, whereas lower-expertise consumers are better served by a need-based interface. Von Hippel [42] argued a programming interface is more efficient for experts in computer technology, and professional designers who offer original designs for customization should be provided with a different interface and a set of different tools within the same toolkit when compared to ordinary consumers who codesign the final products.

3 A Model for Evaluating Web-Based 3D Mass Customization Toolkits

Based on the literature review, we propose a framework – an online 3D mass customization toolkit evaluation model – to evaluate online 3D mass customization toolkits with the focus on consumer experience as well as the underlying technical supports and their influence on the design of 3D toolkits (Fig. 1).

The centre of the evaluation model is the toolkit design. This is driven by the underlying technologies, which offer features or limitations to the toolkit design. The interaction design defines the process of customization, while the solution space provides the design possibilities. In addition, individual differences are also an important factor to evaluate because they help to create a satisfying experience for different consumers. In this sense, the evaluation model has been designed from four perspectives: solution space design, interaction design, supporting technologies (i.e. 3D modelling technologies and web technologies) and individual differences.

3.1 Solution Space Design

The solution space in this model is used to evaluate how diverse and how large the solution space is, i.e. the variety and quantity of potential designs a toolkit can provide. It is concerned with two aspects: the types of customization options

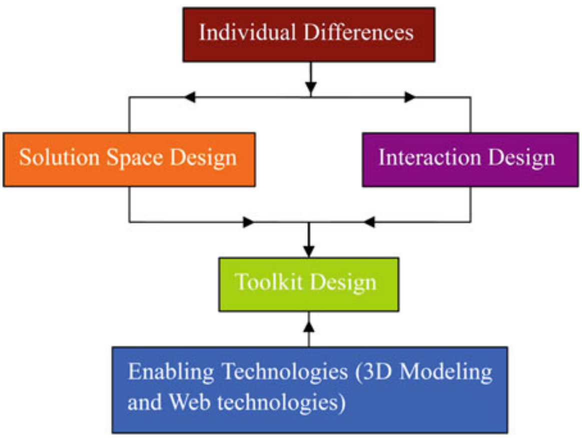

Fig. 1 Online 3D mass customization toolkit evaluation model

a toolkit provides and the size of the solution space. The types of options could be veneered, modular, parametric or generative alternatives when considering the approach to mass customization and then either functional or aesthetic options when considering the purpose of the product changes. The size of the solution space is usually represented by the number of potential final designs a toolkit can provide.

3.2 Interaction Design

The interaction design criteria here represent the evaluation of a comprehensive process. It does not only include interactions between consumers and the toolkit but also refers to interactions between consumers as well as interactions between consumers and manufacturers. Further, interaction design does not only consider the process of consumer participation but also considers how a toolkit should respond and adjust itself to consumer participation. The criteria for evaluating the interaction design are listed in Table 1.

3.3 3D Modelling and Web Technologies

The evaluation criteria from the 3D modelling technology lead on from the literature review and are broken down into four evaluation categories:

- The representation modelling scheme. These can give us insight into what features are offered to the toolkit design.
- The level of the model parameterization. This directly enables the toolkit to offer both interaction design capabilities and the existence of the solution space. The level of model parameterization can vary from a very basic level with simple transformations (such as scale, rotation) to a high level with support for radical changes to the shape of the product (changing the actual shape, adding holes, additional geometry, etc.). The level of parameterization is closely connected with the representation scheme.
- The level of designer's support for modelling and uploading new designs. This shows how much effort a designer applies to produce a new parameterized model and to make it available to customers. For example, generative modelling for boundary representations typically requires programming a new applet or plug-in to produce a design instance for the given set of parameters. On the other hand, function representation allows for a simple save and uploads procedure as the representation itself supports a high parameterization level.
- Required web technologies. Here we distinguish between basic toolkits with HTML and JavaScript implementations, advanced with Java applets and highly 3D interactive with HTML5 and WebGL employed. The required technologies can influence how the site can be viewed (e.g. on smartphone/tablet or PC) which can further affect the consumer experience.

Table 1 Evaluation principles and guidelines for interaction design of toolkit

Categories	General principles	Guidelines
Procedure design	Provide an engaging and autonomous design procedure and support consumers' "trial-and-learning"	Products that require customer creativity should be customized in a flexible design procedure Products that require functionality customization should follow a top-down hierarchical procedure Provide consumers with enough information to let them know which step they are currently in and how many steps ahead to finishing the customization Provide step-by-step tasks with increasing challenge Allow consumers to save their design half way through and come back later to complete it Allow consumers to compare different versions of their design to help them to select the one they prefer
Design guide	Provide clear and easy-to-understand guide and support as needed for the consumer at all stages of the customization process. Consumers should be inspired and encouraged for their innovation	Provide libraries of standard modules to help consumer focus their creative work on those aspects of their design that are truly novel Provide a preset design at the starting point of customization which helps to make the process more accessible Provide real-time help in order to create a safe and supportive environment Use taglines to encourage consumer's experimentation and innovation Provide "how-to" tutorial videos, help menu or clickable paths to further explanations Provide choice navigation and prioritize all customizable options
Direct manipulation	Provide consumers with the sense of control, and allow them to directly manipulate the 3D model	Allow consumers to directly manipulate tools or 3D models for customization Provide instant feedback of consumer's choices to give them a sense of control
Collaboration design	Provide communication opportunities among consumers, and encourage them to share, create and learn together	Provide online community, e.g. online chat room for instant communication Provide galleries of consumer-created works to inspire consumer design creativity Provide opportunities for consumers to leave comment or to assess contributions from others Provide a historical record of work and progress of consumer collaboration around a shared interest

3.4 Individual Differences

Individual differences here are used to assess the ability of a toolkit to consider each consumer's differences in previous experience, knowledge, ability and skills. Typically, an adaptive approach for toolkit design is required in order to design a toolkit tailored to each consumer's differences. This can be achieved through three approaches:

- Provide different starting points by assessing consumer's previous experience of using the toolkit – the toolkit can "remember" previous difficulties or successes for consumers to complete a task and modify the solution space and interaction design based on the frequency and success of previous attempts.
- Provide multiple pathways to achieving a task – consumers should be able to choose their own pathway through to customize a product.
- Provide assortment matching, i.e. automatically recommend configurations for consumers by matching their needs with characteristics of existing solution spaces [37].

4 A Heuristic Evaluation of Online 3D Toolkits

In order to better understand the proposed evaluation model for online 3D MC toolkit and the specific principles developed in this study, a heuristic evaluation was applied to two online 3D MC toolkits design: Sandboxr[1] and Nervous System[2].

A heuristic evaluation is an inspection technique which aims at identifying usability problems associated with the design of user interfaces by applying a set of predefined evaluation principles [32]. A number of studies also confirmed that heuristic evaluation helps designers to find important classes of problems that are not always found with user testing [23, 24]. Due to its flexible nature of application, heuristic evaluation has been adapted to a range of specialized domains, including game design [35] and e-commerce website design [19]. In this study, heuristic evaluation was adapted to evaluating online MC toolkit design.

Sandboxr is an online 3D MC toolkit allowing consumers to create customized 3D printed figures of video game characters. It applies a modularity approach which allows consumers to select different parts, i.e. modules of the product and assemble them to design a final product. Nervous System follows a generative approach to customization which creates computer simulations or algorithms to generate designs.

Sandboxr provides option lists that allow consumers to choose the design they want. In particular, all the options in Sandboxr are predetermined by designers or

[1] https://sandboxr.com/.

[2] http://n-e-r-v-o-u-s.com/.

manufacturers, which means designers or manufacturers retain the ultimate control over the design of the product. In this case, the size of the solution space is limited by the number of modules that designers or manufacturers allow consumers to customize and the options they provide.

Nervous System on the contrary offers more design freedom and creativity to consumers. Nervous System provides a set of tools that allow consumers to directly manipulate and modify the structure of the 3D model in real time. However, the generative approach taken by Nervous System means that each of their designs is the output of a computer program. Each application on the Nervous System website therefore needs programmers to write code for their implementation, which is not easy or flexible for generating more designs in a short time.

Regarding the interaction design, the two toolkits follow some of the guidelines identified in Table 1, but also fail to follow others. Instead of letting consumers design from scratch, both toolkits provide a preset design as the starting point. This helps to make the process more understandable and accessible for consumers. Sandboxr employs a predesigned customization procedure, i.e. consumers have to follow a strict order to customize a game figure. A timeline is used to tell consumers which step they are in and how many steps remain until completion. Nervous System provides a flexible design procedure, but it does not provide enough information to let consumers know which step they are in. Therefore, it is easier for consumers to get lost especially considering it has a vast solution space. Sandboxr does not allow consumers to save unfinished designs, and it provides no way for consumers to compare different design ideas. On Nervous System website, consumers can name their design and save it to a database at any time. They can return later and edit the saved design to complete the order. In this case, Nervous System provides consumers with more support for their creativities.

The direct manipulation of the 3D model on Sandboxr is limited. Consumers can only rotate the 3D model but not zoom in/out or change the structure of the 3D model. After consumers make the decision at each step, it takes a while for the toolkit to show the outcome. Nervous System gives more freedom to consumers. It allows consumers to directly manipulate the 3D model and modify its shape and structure. Feedback of the consumer's customization changes is instant which gives consumers a strong sense of control.

The limitation of consumer interaction to a large extent is because of the 3D modelling technologies the toolkit employs. Sandboxr employs traditional textured polygonal meshes as their geometric model representation. The model parameterization is limited to size selection. Nervous System uses polygonal meshes to represent geometric models. It provides a very high level of parameterization. Each model has to be generated from scratch by generative modelling software tools rather than traditional CAD design tools. Here, the designer has to closely work with or to be a software developer to properly implement the generative procedures in software. Nervous System is also a very advanced toolkit from the web technology point of view, incorporating several scripting languages and WebGL.

Despite providing an adaptive approach to toolkit design ensures the usability and accessibility of toolkits for consumers with different skills, experience and knowledge, neither Nervous System nor Sandboxr considers individual differences among the actual consumer group. However, mass customization is currently still at an early stage of development. Technical limitations and the lack of proper design strategies mean that an adaptive approach to toolkit design is currently still just a theory. It is expected that future toolkits will meet different consumer's needs and requirements.

5 Conclusion and Future Work

In this paper, we have provided an overview of existing studies in MC toolkit design, giving particular focus to online 3D MC toolkits and the consumers' interactions with the toolkits. Based on this review, we have proposed an evaluation model, which attempts to provide a comprehensive understanding of 3D toolkit design from four aspects: consumer, solution space, consumer-toolkit interaction and technological support. Specifically, individual difference, solution space, interaction design, 3D modelling technology and web technology constitute the key dimensions for evaluating 3D MC toolkits. Despite a fair amount of efforts that have been devoted to theoretical research, current 3D toolkits are still at an early development stage, and a number of research questions need to be addressed as directions for future research.

Previous research has found that individual differences in knowledge, skill, creative talent and previous experience require different design strategies for solution space design and interaction design. Despite a number of studies suggesting how to adapt toolkit design to different consumers, few efforts have actually been made to apply them into practice. Therefore, research questions that we suggest should be considered in terms of individual differences include:

- In addition to knowledge, skill, creative talent and previous experience, what other individual factors would influence toolkit design? For example, gender? Age? Income?
- What is the best way to discover individual differences, especially for new customers? An explicit approach, for example, could directly ask the consumer's gender or preferences or an implicit approach that the toolkit adapts itself to consumer capabilities without letting them know.
- Given a set of identified differences, how should the toolkit adapt itself to best suit these?

Solution space design is understood as all the possible designs a toolkit can provide. Specifically, the size of the solution space and the types of options are two main concerns. Here we argue that the size of the solution space is not a single dimension. It is influenced by a number of factors, such as the type of product and the approaches of customization. For example, the number of options for customizing the aesthetic aspect of a product may be different from the number of options for customizing the functional aspect of a product because the function of a product may be restricted from a practical purpose as well as safety or legal concerns. Given these considerations, we suggest that future research questions which should be considered for solution space design include:

- What are the factors that influence the size of the solution space?
- What are the efficient ways of organizing options for different customization approaches, i.e. veneer, modularity, parametric and generative approaches, to avoid mass confusion?
- What auxiliary information should be provided to help consumers understand each customizable option, e.g. how to interact with it and what effects it will bring to customizing the product?
- Considering individual differences, what is the best way to adapt the solution space design to different consumer's needs and preferences?

Interaction design refers to the process of the consumer interacting with the toolkits and customizing the product. Most MC toolkits are lacking in basic HCI principles [44]. We suggest the following research questions for future research in interaction design for MC:

- What HCI principles should be followed by mass customization toolkit design?
- What support can be provided to the consumers to help them understand the process of interaction and customizing the product?
- What are the effective ways to encourage consumer's interaction and creativity while customizing the product?
- Considering individual differences, what different interactive strategies can be applied to difference consumers or consumer groups?

The design of a toolkit is closely related to technical development. In particular, 3D toolkit design is a special area which is quite different from 2D toolkit design in terms of the visual representation of products and the way consumers interact with the toolkits. Therefore, 3D toolkits bring different experiences to consumers when compared to 2D toolkits, which also have higher requirements for the technical support, especially for the development of 3D modelling and web technologies. Different technologies bring different capabilities and restrictions to toolkit design, many of which can only be improved by technical breakthroughs in the future. Therefore, future research questions in terms of enabling technologies include:

- What are the most intuitive interface elements for an MC model and how can they be supported by the modelling representation scheme? From a technical standpoint, one of the easiest ways to technically provide access to a model's parameters is through slider interface elements, but this is not necessarily the most intuitive from the user's standpoint.
- How can MC interfaces make better use of established and emerging technologies and portable devices, including touchscreen, gestures or VR?
- How could a collaborative interface be presented for MC, reflecting requirements and views of different audiences? This would allow a professional designer and client to look at the same artefact but see them in different ways and interact with them through a different interface in different ways.

- Given recent advances in multimaterial 3D printing hardware and supporting model representation schemes, how can a viable and intuitive interface be made for multimaterial products and how can these be made available for MC?

This study helps us understand the current state of MC research especially in terms of toolkit design in academia. However, most current studies take a theoretical approach rather than an empirical approach to propose their research findings. In other words, researchers draw their conclusions based on their knowledge in related areas (e.g. HCI, psychology, etc.) or their analysis of a few online MC toolkits rather than actually observing consumers using toolkits to customize a product or testing their findings on consumers. Therefore, in the future, we expect to conduct user studies to test what we find in this study and conduct empirical studies to discover the answers to the research questions we proposed above. In the end, we hope to construct comprehensive and systematic design guides for online 3D mass customization toolkit design.

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Front-End/Back-End Integration in Mass Customization: Challenges and Opportunities

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Abstract Many mass customization challenges can be ascribed to insufficient integration of front-end (e.g., customer choice navigation processes, product configuration, user interfaces, and customer behavior patterns) and back-end (e.g., order management, purchasing and production planning and control) systems. To succeed as a mass customizer, customer/manufacturer integration is critical. This paper provides in-depth insights to integration challenges and opportunities based upon a case study of four manufacturing companies. For solution space and product development, high uncertainty in new idea generation, lack of systematic product and solution space development, and limited knowledge of what is the "right" solution space are identified as challenges with opportunities for improvement. Regarding choice navigation, many companies have limited direct contact with end customers due to sales through dealers and resellers. Associated inefficient information flows are another challenge. The companies acknowledge opportunities related to advisory support during the sales process, as well as enhanced external collaboration with, e.g., complementary actors. With respect to back-end systems, inefficient information flows also occur here. This, in combination with a large number of freestanding ICT systems, results in cumbersome production planning and execution. This is complicated even more by incorrect basic data. Finally, there are major opportunities in automatic visualization and efficient utilization of key information from the entire value chain. In addition to outlining several directions for further research, the paper provides in-depth, company-based insights to key integration development areas, which managers may use when developing their own mass customization practices.

Keywords Choice navigation · Solution space · Planning and control · Digitalization · Visual factory

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1 Introduction

By utilizing mass customization principles, many European companies are able to compete globally despite the high cost levels in the West. In Norway, four companies have worked consciously with mass customization over several years. The companies manufacture home and office products in metal and wood, such as windows and doors, office chairs, kitchen ventilators, and waste bins, to the end customer's (unique) specifications. Even though the companies perform well, they face multiple challenges and see potential for improvement in various areas. For instance, staffing issues, lack of coordination, and disrupted product and information flows result in reduced deliverability and excess capacity in periods. Many of these challenges can be ascribed to insufficient integration of front-end (e.g., customer choice navigation processes, product configuration, user interfaces, and customer behavior patterns) and back-end (e.g., order management, purchasing and production planning, and control) systems.

Insufficient front-end/back-end integration in mass customization is likely widespread, as companies often pay extra attention to specific technologies or aim for the ideal product mix, rather than taking an integrated, overall perspective. Much of the research on mass customization reflects a functional focus, by considering, e.g., product design, marketing, and manufacturing individually [1]. However, in order to truly succeed as a mass customizer, customer/manufacturer integration is key [2]. For many companies, there is still an untapped potential in tighter integration of front- and back-end systems; i.e., linking customer specifications with operational activities [3].

In order to realize their full mass customization potential, the four Norwegian mass customizers have embarked on a joint research project, *Custom*^{R}, to find better solutions to integrate front- and back-end systems in their specific context. As part of the project, the companies' customer journeys and order management processes have been mapped, to identify current challenges and opportunities pertinent to front-end/back-end integration. The purpose of this paper is to present and discuss identified challenges and opportunities faced by the four companies, such as their reliance on dealer networks, which severely influences the customer's exposure to the solution space and how efficient order information is transferred to the shop floor. In accordance with the Custom^R research framework [4], the findings are sorted in choice navigation, solution space and product development, visual factory, and back-end systems, respectively.

2 Methodological Considerations

In the Custom^R research project, the action research method is employed. In action research, researchers and a problem holder (in this case the four Norwegian mass customizers) collaborate in solving real-life problems while they keep a research interest in mind [5]. The idea is to create a mutual dependence on the researchers' and the problem holder's skills and competences, which in turn generates new knowledge for both parties [5]. The companies aim to improve their abilities to develop tomorrow's products and services, based on real customer choices and usage patterns, through tighter integration of front- and back-end elements. The project will address these needs by developing integrated solutions in the interface between customers' preferences and the internal processes of companies in close collaboration with research partners.

The presented challenges and opportunities have been identified through a series of workshops, semi-structured interviews and observations at the case companies over a period of 6 months. Some industry interviewees and participants have been chosen specifically for the topics covered in the different sessions (e.g., sales manager partaking in choice navigation mapping), while some (e.g., managers and senior project engineer) have followed the entire process.

The case companies differ in terms of design, marketing, sales, modularization, manufacturing, distribution, etc. While some are more mature mass customizers, they all share the need to integrate and visualize front- and back-end operations to a larger degree. Table 1 summarizes some of the companies' characteristics.

3 Research Framework

This research is based upon the Custom^{R} research framework [4]. The rationale behind the framework is that while there is a significant amount of research dealing with major distinct areas of mass customization, such as choice navigation, solution space, and robust processes [6], there is limited research on the integration of important functions and activities in mass customization. Arguably, there is a need for tighter integration between customer preferences and internal processes, i.e., the front-end and the back-end. The framework presumes that the front-end and back-end should be tightly integrated by the choice navigation and solution space, e.g., by the use of product configurators, and that big data should be used to continuously monitor and refine, if necessary, what is offered to the customer and the processes in place to deliver what is offered. Core elements of the research framework are briefly described below.

Solution Space Being able to specify products is essential in mass customization. Too few varieties often results in loss of sales. At the same time, variety comes with a cost [7]. In mass customization, there is a tendency to quickly reach an astronomical number of theoretical product variants. However, often only a fraction of the variation offered to the customer is exploited. This can be caused by, e.g., poor choice navigation, where one offers sufficient variety but is unable to communicate this to the customer, or that the offered variety is not in demand by customers; i.e., one is offering the wrong products [8]. The solution space must be carefully defined to provide the right level of product variety. The main identified solution

Table 1 Case company characteristics

Product	Doors and windows	Office chairs	Kitchen ventilators	Waste handling and cleaning
Solution space	"Infinite" (only limited by physical size)	More than 1 billion	Thousands (full NCS/RAL color range)	Thousands (full NCS/ RAL color range)
Primary sales channel	Builders' merchant	Office furniture dealers	Kitchen suppliers	Large-scale projects
Important stakeholders	Carpenters, architects, end customers	Interior architects, company buying departments, end users	Kitchen suppliers, interior architects, end customers	(Interior) architects, project owners (e.g., airports, schools), end users
Demand and production characteristics	Mostly make-to-order, some standard dimensions make-to-stock due to seasonality and predictable demand, batch production for large orders, otherwise one-piece flow	Make-to-order, varying order sizes (from one to hundreds), satisfies in average more than 1000 customers per day, one-piece flow	Make-to-order, one-piece flow	Mix of make-to-order (project orders) and make-to-stock (predictable demand), mostly batch prod.
Product variety determinants	Glass, insulation degree, shape, size, crossbars and posts, opening possibilities, hinges and fittings, sealing and colors	Gas lift, wheel base, seat width, back height, armrests, headrests upholstery method, metal and textile colors and textures	Model type, material, size, color	Model type, color/design

space and product development challenges and opportunities are related to idea generation, lack of methodical development, solution space dimensioning, and awareness, respectively.

Choice Navigation Choice navigation is about supporting the customer in choosing the solution that maximizes customer value within a predefined solution space [9]. Solutions for choice navigation are essential for many reasons. It guides the customer in locating the product or service that best fits his or her preferences. Also, the process of configuring can itself be considered a customer experience [10]. Moreover, the customer's choice is a basis for technical specifications, like bill of materials, production sequences, and technical drawings needed to provide the required product or service [3, 11]. In the face of too many choices, the customer will often experience choice navigation as a cost, due to, e.g., the time it takes and frustration from cumbersome solutions [12, 13]. Therefore, it is important to minimize the complexity of choice navigation [6].

Back-End Systems Front-end/back-end integration is largely dependent on integrated ICT systems that render possible rapid and automated order management, real-time order status, and feedback between production, product/solution space development, and choice navigation. While product configurators and CRM systems dominate front-end systems, a myriad of different systems exist in back-end. Examples of systems include enterprise resource planning (ERP), business intelligence (BI), manufacturing execution (MES), time registration, maintenance and improvements, and freight forwarding. Back-end systems are largely concerned with robust processes, in that they should facilitate efficiency, waste reduction, flow, flexibility, and responsiveness.

Visual Factory In most companies, the access to information is not a problem. While internal back-end systems have an important role enabling efficient exchange and sharing of information across departments, the internal sharing of this information is often inefficient. This poses a challenge in a time where changes become the norm, and input from the front-end is ever more important for back-end efficiency. Increased visibility is a means for increased performance [14]. A visual factory is well organized, tidy, in good condition, standardized, and disciplined. Visual workplace practices drive productivity through empowerment of operators – allowing them to make decisions based on right information available at the right time [14]. Increased digitalization makes it easier to rapidly share information to both employees and visitors in the factory.

4 Challenges and Opportunities of Integration

An overview of challenges and opportunities of front-end and back-end integration is presented in Table 2. Findings are categorized according to four key areas of integration and are further described in the text below.

Table 2 Identified challenges and opportunities of integration

Key area	Challenges and opportunities
Solution space and product development	High uncertainty in new idea generation Lack of systematic development Limited knowledge of "right" solution space
Choice navigation	Limited direct contact with end customers Inefficient information flows Need for advisory support Enhanced external collaboration
Back-end systems	Inefficient information flows Cumbersome production planning and execution. Incorrect basic data
Visual factory	Major opportunities in visualization of key information Need for automatic information handling Enhanced utilization of visualized information

4.1 Solution Space and Product Development

The main identified challenges and opportunities of solution space and product development are related to idea generation, development methodology, and knowledge about the solution space.

High Uncertainty in New Idea Generation Customers' needs and preferences vary in different markets. Consequently, there is a lot of uncertainty when it comes to generation of successful ideas for new product families. Current idea generation is primarily based on catalogue surveys and exhibitions, after which companies mimic expected trends and add their own twists before products are pushed into the markets. However, the companies see a potential in analyzing trends in, e.g., sales data more systematically, to discern order winning product features that can be further exploited in idea generation. The development of concepts based upon facts and analyses may help to reduce uncertainty at an early stage and ensure successful ideas.

Lack of Systematic Development Several of the companies have expressed a concern regarding their lack of product development methodology. Today, development projects take different forms. Some are large, systematic, and planned, such as upgrading of existing product families with respect to fit, form and/or function for various reasons (e.g., improved ease of assembly, rules and regulations, trends), or joint R&D projects with other partners (e.g., Custom^{R}). Others are unplanned opportunities, such as sudden ideas of new product families ("epiphanies"), input and inquiries from customers and collaborators, or availability of new components that can be introduced to improve products. The companies typically depend on a few key persons with development skills. At the same time, often the development responsibility is not assumed by one person. Further, there is a lack of development plans and project execution models to guide the development projects. A systematic approach may improve the chance to take both customer and production perspective into consideration throughout the entire development process.

Limited Knowledge of "Right" Solution Space The solution space is closely related to idea generation and product development, as new products and adaptations will expand and/or alter the solution space. As mentioned, the customers' needs and preferences vary in different markets, and the companies have little systematic knowledge about what is the right solution space for different target groups. Further, the companies acknowledge that it is important to think through the product architectures thoroughly and define their product ranges and their limitations early, as the solution space may influence both manufacturing and marketing/sales. Some have experienced that additions made to the solution space have been easy to sell, but not necessarily easy to produce efficiently. Knowing such consequences of solution space alteration upfront is a key challenge. There is an unexploited potential in the further inclusion of customer preferences in the development of the solution space. The continuous development and tuning of the solution space is an opportunity that could be exploited further.

4.2 Choice Navigation

The main identified challenges and opportunities of choice navigation are related to customer contact, information flows, customer advisory, and collaboration with partners.

Limited Direct Contact with End Customers The companies primarily sell their products through resellers and dealers, and have limited direct contact with end customers and users. While intermediary dealers bear financial risks associated with invoicing and handle last-mile distribution, complaints, and so on, they also serve as filters in that the companies do not have full access to information about end customer asking price, satisfaction and needs, feedback, and trends. There is a potential in capturing and analyzing such information to enhance understanding of customer needs. Internet-based tools, such as product configurators, web shops, web communities, and social media, are typically used to reach and communicate with end users. Generally, the same tools may be used as a source of intelligence for learning purposes. For instance, user data from product configurators can be extracted and analyzed to enhance a company's understanding and knowledge about customer preferences and serve as input to further development of both the solution space and the product configurator itself. This, however, is not straightforward when selling through an intermediary partner, as companies must develop product configurators and other tools that serve both dealers and end customers. These solutions need to be adjusted to the specific needs of different target groups. At the same time, different configurator solutions still need to be integrated to be able support a dialogue between different actors; i.e., dealers should be able to easily get access to a product configuration of a specific customer, even if this was started in direct contact with the manufacturer, to be able to provide customer support, manage transactions, etc.

Inefficient Information Flows As sales toward end customers is often handled by resellers and dealers, the overall sales process is characterized by high complexity. There are many actors involved, and many operations in the order management process involve time-consuming manual registration and distribution of information. Typically, there is substantial communication involved to define right product solutions and delivery dates, which is carried out over e-mail and telephone. Currently, this information needs to be registered manually in various freestanding systems, in order to calculate the correct price and offer an accurate delivery date to the dealer or reseller, which communicates this to the end customer. The companies acknowledge that there is a potential to reduce the number of systems and to better integrate them. Further, they should develop tools to better support sales. The implementation of product configurators could help to facilitate the sales process and create better predictability and visualization. Configurators may also provide better support to efficient navigation of the solution space, contributing to improved customer experiences.

Need for Advisory Support Several of the companies have a strong profile as a “knowledge partner” to their customers, providing expertise to customers throughout the products’ lifecycles, from selecting the right product to installation, use, and maintenance of their products. Some kind of advisory throughout the choice navigation is often a necessity, to ensure that the products fully meet, or even exceed, the expectations of the customers – thereby maximizing customer value. This type of value-adding advisory service can be further systematically developed. For instance, efficient advisory could be part of a product configurator solution. Based upon defined customer needs, the configurator should be able to propose a set of suitable solutions, thereby limiting the communicated solution space in order to ease the product selection. In addition, it could provide useful hints that aid the customer in making good configurations and even offer “fun facts” and other information that underline the company’s position as a knowledge partner. Hence, there is an opportunity in using configurators to provide professional, value-adding advisory services.

Enhanced External Collaboration There is a major potential in developing partnerships with other niche manufacturers and suppliers that offer complementary products. Customer choice for one product is often dependent upon other product choices, i.e., chairs and tables, windows and doors, and ventilators and kitchen furniture. Being able to offer a combination of several products from different suppliers coordinated in one delivery can serve as a value-added offering to customers. Another opportunity is to work more closely with key stakeholders having customer relations, such as architects, interior decorators, and construction engineers. This may involve offering storage of product data that can easily be used by others, such as BIM and 3D-drawings.

4.3 Back-End Systems

The main identified challenges and opportunities of back-end systems are related to flow of information, production planning and execution, and basic data.

Inefficient Information Flows As for front-end systems, the companies have many freestanding back-end systems, and inefficient information flows in the front-end interlock with the back-end. As noted above, incoming orders are typically manually checked up to available production capacity in order to define a suitable delivery date. The production planning also involves a lot of manual registration and transfer of information between different systems (see below). Further, during production, there is little registration of progress, which makes it hard to communicate actual progress and capacity to the front-end. There is a potential to improve access to correct information regarding available capacity in production. To avoid manual handling, more automation is needed. This is especially important for customers using configurators, who need an immediate confirmation of delivery date when placing their orders. There is further potential to use progress information in real time, both internally and to customers. For instance, performance information should be available to operators, so they can see how they perform according to plan.

Cumbersome Production Planning and Execution After sales/marketing have checked capacity and registered the orders in the ERP system, most of the companies generate rough production plans based on the registered orders. However, usually these rough plans cannot be used directly in production. Instead, the plans are manually adjusted due to, e.g., change orders, failed credit checks, overbooking, leveling of production, and product-dependent bottlenecks that are not taken care of automatically by the systems. Thereafter, these adjusted plans are transferred to production. In some cases, this involves transferring a copy of the adjusted order list to a manufacturing execution system (MES), which carries out detailed scheduling and executes orders. This transfer typically happens once a day. After the transfer, changes in the ERP order will not automatically be reflected in the MES. Thereafter, when an order is put into production, the ERP system is checked to see if the order is still valid. After production start, changes may still occur due to, e.g., overbooking of bottleneck resources, specific customized features outside the defined solution space, and customer credit control. There is a potential to develop better decision support so that production is only initiated for orders that can be fulfilled within the original plan in order to avoid unnecessary changes in the plan. Moreover, an order should automatically be registered in the ERP system as the customer places his order, and production plans should automatically be generated from the ERP system. Plans may be further transferred to a MES system and updated frequently. This would require more registration points in production, with integration between programmable logic controllers (PLC)/MES and MES/ERP.

Incorrect Basic Data Without high-quality data, there is generally a risk of offering products that are difficult, or even impossible, to deliver with correct specifications, at the right time and cost. Many of the companies experience challenges with incorrect basic data regarding, e.g., article numbers, product structures, and process times. This propagates to, e.g., order management, where incorrect basic data may skew the theoretical production capacity taken as a starting point when communicating delivery times with customers. The companies acknowledge that in order to communicate viable solution spaces, correct prices and delivery dates to customers, create and execute reliable production plans, and communicate goals and progress on the shop floor, product and process data need to be correct and consistent. Adaptations of the solution space must be reflected in the basic data, and the data needs to be maintained to be in conformance with, e.g., GTIN (Global Trade Item Number) and other product databases.

4.4 Visual Factory

The main identified challenges and opportunities of visual factory are related to visualization, automation, and utilization of information.

Major Opportunities in Visualization of Key Information In the companies, there are major opportunities in applying various visual tools. Examples include visual meeting areas for operator information exchange, visualization of work instructions and documentation, visual production and quality control, visual process indicators and progress control, and visual mechanisms for registration and follow-up on improvements and major achievements. The companies have all initiated improvement projects related to such topic.

Need for Automatic Information Handling To avoid manual and time-consuming information handling, (semi)automatic updating of status is a critical success factor. Visual displays should be based upon data available in current systems. As mentioned previously, data may be automatically captured at several registration points in production. Sales and customer relationships departments may use real-time information about production progress of individual orders to provide status updates to customers.

Enhanced Utilization of Visualized Information Availability of information is not enough; it should be utilized in the best way possible. The companies see a potential to utilize information further, to enhance customer value, as a tool for operators to improve control, and in fulfillment of orders. Information may be shared between departments to show the need for support in other parts of the production. The production flow may be visualized and communicated to employees, who can be supported by visual aids to make the best preventive actions, or corrective actions when something unexpected occurs. Key performance indicators showing efficient flow may be established, providing feedback to operations and sales. Further, there is a need to develop better decision support in capacity planning, work balancing, and delivery date definition. A visual dashboard may be developed showing boundaries and loading of production bottleneck processes. Information regarding prioritized orders and changes in production plans may be better communicated across departments. Finally, there is a potential to utilize information more in the work with continuous improvement. For instance, data can be analyzed after a production period to identify points of improvement. All employees should participate and contribute to further improvements.

5 Discussion and Conclusion

Mass customizers often experience insufficient integration between front-end, customer-centric processes and back-end production systems, although such integration is crucial for efficient adoption of a mass customization strategy. In order to add further details to integration issues and potential development areas, this paper highlights key challenges and opportunities of front-end/back-end integration experienced by four Norwegian mass customizers. Four key areas are investigated: Solution space and product development, choice navigation, back-end systems, and visual factory.

The customer perspective is essential in the development of new products and the solution space. More systematic and structured approaches that ensure high degree of customer integration are therefore needed. The process of defining an appropriate solution space can be further developed, especially in terms of including product attributes along with which customer needs mostly diverge, as suggested by Salvador et al. [6]. Besides the development of systematic methods for defining what the "right" solution space, suggested further research also includes new approaches and tools for collecting and handling data on customer preferences and requirements. Enabled by digitization, major opportunities lie in applying technology to capture large amounts of such data, and analyze it in combination with production data, to continuously develop and tune the solution space in a systematic manner.

Efficient choice navigation is critical for mass customizers, to provide high customer experience at a suitable level of complexity [6, 10]. There are major integration opportunities related to the adoption of product configurators, as such tools typically involve direct interaction with customers and enable efficient integration of digital information flows. A challenge for companies that sell through intermediaries (i.e., dealers and resellers) is that they lack direct contact with end customers. With respect to product configurators, many companies also need to develop solutions that are adapted to the needs of different target groups – both resellers and end customers. Design methods and tools for efficient choice navigation solutions may be further developed, especially regarding how to achieve a high level of customer experience while catering to multiple channels, involving both dealers and end users. Further, since configurators allow companies to efficiently capture and get access to a large amount of customer data, there is a need for more research on the integration of configurator data, i.e., how to utilize this data in developing the solution space and new products.

Major challenges regarding back-end systems are related to inefficient manual handling of information in combination with limited integration between existing systems, especially resulting in cumbersome production planning and execution. Seamless automatic information flows throughout the value chain, from customer orders to product delivery, combined with enhanced decision support, may contribute to more efficient planning and control of operations. There is major potential in the integration of product configurators with ERP and MES systems. Future research may deal with how to integrate information flows and automatically capture and utilize large amounts of real-time data for more dynamic planning and control of operations.

Regarding visualization, there is an enormous potential in exploiting new ways of capturing, analyzing, and presenting data, to enhance efficiency in operations and increase visibility of critical information across departments. Visualization is critical for mass customizers to stay flexible and alert on customer changes and to help operators take right decisions [14]. With increased digitalization, visual tools that ensure efficient handling and communication of available information, through data analysis and presentation, may be further explored.

Generally, many issues of insufficient integration may be dealt with by exploring opportunities of process digitalization and advanced ICT. Increased digitalization makes it easier to rapidly share information to both employees and visitors in the factory. It enables seamless transfer of information from customers' choice navigation and use phases, e.g., as product specifications directly uploaded to 3D printers. The application of new solutions for capturing, analyzing, and presenting data, supporting seamless information flows, implies a major potential for efficient integration. Product configurators play a key role in realizing the mass customization strategy in many companies, providing a tool for efficient integration. However, looking "beyond" product configurators, there are many other relevant technologies and solutions, especially related to visualization and advanced planning and control, that mass customizers should exploit further. Showcases and live demonstrators of smart connected features for efficient front-end/back-end integration are necessary to show concrete examples of how such applications may be applied in practice, for enhanced learning and value creation.

Besides adding further details to major issues of integration, this research points out several directions for further work, which other researchers may use to develop new knowledge and solutions for efficient integration. Specifically, emphasis on the development and test of new solutions enabled by increased digitalization that exploit opportunities of integrated information flows through the front- and back-end systems of mass customizers is called for. This study also provides in-depth company-based insights to key integration development areas, that managers may use in further developing their mass customization practices and practical solutions to support further front-end back-end integration.

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Design and Development of the CEM-Dashboard: A Diagnostic Tool to Determine Your Current Position and Improvement Directions in Customer Experience Management

Marcel Weber and Arend Hofsink

Abstract Customer experience management is gaining attention from companies in the latest years. Companies realize that it is not anymore sufficient to only meet customers' functional demands but that customers are also in need of a pleasant treatment, personalized attention and communication, trouble-free and smooth operations, and good feelings from interacting and transacting with companies. We call this total set of positive emotions that customers are looking for the customer experience.

This customer experience can be managed as many researchers and practitioners have stated. For this, several model-based approaches for customer experience management have been developed by academics and practitioners, but usually they prescribe actions on a high strategic level and omit to close the PDCA loop with an assessment of the results. Organizations that are looking for specific actions and their effects because of their closeness to the customers, like customer contact centers, mass customization producers, web retailers, and service providers, therefore feel neglected and surpassed by these models.

To fill this gap, we designed and developed a diagnostic and benchmark tool, the CEM-Dashboard, for such companies to determine their current position and improvement directions in their efforts to implement customer experience management in the company and its processes.

Keywords Customer experience management · Design science research · Diagnosis · Benchmark

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1 Introduction

Companies that want to make profit in today's highly competitive and customer-critical global markets will have to take into account that it is no longer sufficient to merely produce qualitative good products or services but have to consider creating total experiences for their customers [1]. Customer experience (CX) is about all cognitive, emotional, affective, social, and physical reactions a customer shows when directly or indirectly in contact with a company, brand, or its manifestations, like an outlet, a shop, a customer contact center, or even an advertisement [2, 3]. The better a customer thinks and feels about a company or its products, the more likely it is that he will be loyal toward and show positive word of mouth (WOM) for this company and its brand(s) in the future [4]. This will inevitably result in a higher turnover and profits for the company when it manages this CX in the proper way [3, 4]. This also applies to mass customization (MC) companies [2, 5–7].

Customer experience can be created and managed [3, 8]. Interested organizations start to become aware of this. We therefore observe an increasing attention from business and governmental organizations for customer experience management (CEM) in the past decade. This draws the attention from both academics [4, 9] and practitioners [10–14] to provide insights for this phenomenon of CEM. Literature on the practice of CEM is however limited to conceptual approaches by practitioners in practice-oriented literature and tends to focus on the practical managerial aspects of customer experience management for large, mostly global operating firms, operating in the B2C. Weber and Oude Elferink [7] make an attempt to engage SMEs as well by developing a diagnostic tool that also provides implementation and improvement directions for these SMEs.

However, all these approaches, although strong in providing relevant implementation actions, fail to complete the so-called PDCA cycle [15] which is universally required for improvement actions. To close this gap, we researched the field of CEM implementation and improvement, both academic and practice, in order to develop a tool that measures the merits of the implementation efforts. In order to enable actions after the check, the tool also provides implementation and improvement directions for the organization that decides to apply the tool. We will name it the CEM-Dashboard.

In this paper we report on this research of tool development, which is a practice-oriented research intended to solve a practical problem in practice with a generic solution based on academic- and evidence-based knowledge [16]. This latter condition distinguishes it from consulting and also from traditional academic research. The structure of this paper, therefore, deviates from traditional academic papers. First, we will describe the research design, followed by a review of the literature on CEM from which design propositions were derived and to finish with the result: the CEM-Dashboard that was validated. We will not elaborate on all details and results of the several steps that were taken in the course of the tool development. First of all, this is because of the fact that some of the steps have been reported separately in other publications – whenever appropriate we will refer to these reports. Moreover, this paper is more about a description of the process of developing the tool than a study in the concept of customer experience management. This concept and its relevance for the MC community have already been elaborated on in our previous works for the MCPC [2, 6]. We will restrict ourselves to only those necessary academic and other insights which are relevant for the tool development.

2 Research Design and Method

In order to develop the CEM-Dashboard – a tool that measures the merits of the CEM implementation actions and to indicate follow-on directions for further implementation and improvement – we followed a seven-step approach and the principles of design science research (DSR) [16]. To accomplish this, we cooperated with two business schools which provided researchers and students for the distinguishable stages of the development.

As a first step (step 1), a literature study was conducted to get a comprehensive view of what CX is and how CEM should be organized and undertaken. Based on these insights, a survey was conducted (step 2) among Dutch organizations to investigate whether these organizations have defined strategies for CEM and its implementation, as well as whether they were undertaking – or have undertaken – actions to implement customer experience management in their organization. In addition, the survey also surveyed the external (market sales and turnover, customer satisfaction) and internal (innovation power, employee welfare) effects, which these strategies and actions might have resulted in.

Based on the survey results, we then selected a sample of 20 organizations that have claimed in being active with CEM. Half of this sample yielded good to excellent results with their CEM efforts; the other half did not show significant effects in their efforts. These 20 organizations were each interviewed (step 3) in order to investigate and verify their progress and results in the implementation of CEM, as well as to get insight in the specific actions that these organizations were or weren't taking to implement CEM. A follow-up literature research and synthesis [17] were conducted next (step 4), to check whether the stated actions we got from step 3 were grounded in academic or evidence-based literature. This resulted in the distinction of "building blocks" for an effective CEM implementation, which we call the design principles [18] for an effective CEM. This set of design principles served as a basis for the design process of the CEM-Dashboard (step 5). For each design principle, we – based on literature – derived a set of probes that can be used to measure to what extent a recommended or mandatory action for effective CEM has been implemented and how effective this action is. These probes were transformed into survey questions. The questions are administered in two simultaneous surveys, one within the participating organization and the other externally in the organization's market (customers). We included customers to validate assertions of managers and the effect of actions. All answers result in quantitative scores that, by means of an arithmetic algorithm, can be used to calculate the total score. These scores can be compared to an ideal score – a score one gets when CEM is ideally implemented and successful – which serves as an indication for the stage of CEM implementation or CEM maturity. The scores can be graphically displayed for the convenience of the organization.

As a next step (step 6) in the design and development of the CEM-Dashboard, the questionnaire and customer survey, together forming the CEM-Dashboard, were tested with some eligible companies for their robustness and comprehensiveness to validate the dashboard. The output of this validation serves as a basis for some redesign activities which will be carried out in the near future as a final step in the tool design (step 7: redesign of the CEM-Dashboard).

3 Research Process Results

3.1 Step 1: (Initial) Literature Review

The systematic literature review was intended to explore the concepts of CX and CEM as a basis to determine whether Dutch organizations in the northeast region of the Netherlands can benefit from these concepts. From a total of about 200 titles of journal articles, books, and essays on the subject of customer experience or customer experience management, 75 proved to be relevant and insightful for our purpose. Based on this systematic review, we have recognized that customer experience management can be a new way for organizations to create a competitive advantage, simultaneously creating more value for their customers. The insights were depicted in a conceptual framework for a better understanding of the concept, identifying several important elements that have to be taken into account in customer experience management, i.e., the CX can be distinguished in types, levels, and strengths of experience that, as a whole, determines the total CX; the tacit and measurable outcomes of a great customer experience for the firm; the methods to measure CX; the conditions to execute customer experience management; the possibilities for customer experience management 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 customer experience management. This latter element of the framework bridges customer experience to customer co-creation, in particular the co-creation of experiences in NPD. This step resulted in two conceptual papers, on which was presented at the MCPC 2014 [2] and the other one as a report for the northeast region of the Netherlands [19].

3.2 Step 2: Survey on CEM Implementation in Dutch Organizations

With the results of our literature review, a survey was designed to investigate the penetration, diffusion, and effects of CEM among Dutch organizations. The survey was set out among 800 organizations in the summer of 2013. A total of 190 organizations responded to the survey, about 11% (21) of them being active in mass customization. From the responding organizations, about 20% is unaware of or inactive in CEM; about 40% states to do something in CEM, although limited because of resources and beliefs. The other 40% states to be very active in CEM. The majority of the 80% of organizations which are active, whether very active or on a low level, are B2C organizations. B2B organizations seem to be less eligible for CEM implementation. About half of the CEM-active organizations claimed to be successful in terms of higher sales, turnover, and customer and employee satisfaction, leaving the other half less successful (no increases) or even unsuccessful. It is our duty to point out that from these findings it could not be evidenced whether CEM is responsible for the economic and organizational successes demonstrated. The results and discussion of this survey were reported locally [19], suggesting an opportunity for B2B companies to improve customer relationships by focusing on CEM. To support the awareness for and implementation of CEM, the CX-Liner [7] was developed.

3.3 Step 3: Interviews

Because the results of step 2 did not meet our expectations that CEM will lead to success, and, in fact, were contradictory, we decided to interview a sample of the organizations that had participated in the survey. We selected 20 organizations of the respondents that had supplied their contact for future research. They varied in size and business, but we made sure that half of them were successful with CEM and the other half indifferent in success or even unsuccessful. We intended to focus on the suggested causality of CEM for an organization's success. Therefore, we had to find out what these organizations were doing correct or wrong. The interviews took place in the fourth quarter of 2013 and were carried out by several researchers of the Windesheim Business School in Zwolle.

One of the important findings of this study was that the majority of the interviewed organizations claimed to be active with CEM while being unaware of its meaning and its merits. For instance, we found out that most of them confused CX with functional customer satisfaction (CS), believing that only functional fit, like product and service quality, matters for customers. Another common confusion was the differences between CEM and customer relationship management (CRM). Nearly all interviewed organizations hardly paid any attention to aspects like customers' emotions and the customer journey. Also, when it came to the measurement of CX, most organizations restrict themselves to CS as customer feedback, while two-third of the interviewed organizations do not even systematically measure customer feedback. Organizations that have a customer contact center or customer service center to address questions, complaints, suggestions, and any other contact that customers need or want with the organization failed to see the possibilities to systematically gather such customer feedback in a systematic way; “big data” opportunities in customer experience hadn’t been discovered yet by these organizations. However, a large part of the respondents was unconsciously doing many activities that are part of CEM in an uncoordinated way, not knowing how to systematically implement CEM. As for organizations that claimed to yield indifferent or even worse success, we found out that this could be attributed to the bad economic circumstances because of the financial crisis. Most of the interviewed organizations also expressed the need to benchmark themselves with peers and the market as a whole when being active with CEM. In sum, we concluded, organizations are in need of a systematic and comprehensive approach to implement CEM and a “measurement tool” to inform them on the effects of their efforts. We decided to make it our mission to develop such a tool.

3.4 Step 4: Additional Literature Research

With that conclusion and mission in mind, we engaged with the Amsterdam Business School to look for a theory- or evidence-based systematic approach to implement CEM and to measure its effects and progress. We judged it to deserve a thorough investigation since no such systematic and unambiguous approach has been presented, yet [3]. Five undergraduates of the business school were recruited to do such a literature review and to construct a systematic approach for the measurement of CEM progress and success in organizations. This literature review resulted in the identification of five “building blocks” of CEM, which are of equal importance during implementation and enjoy broad consensus in academic- and evidence-based literature, although the naming of the blocks and their components may differ among academics and practitioners. They will be discussed briefly in the following subsections.

Brand and Brand Promise(s) Schmitt [20] provides a five-step plan for the optimization of CX, in which the third step is aimed at creating a brand experience. The communication of an organization’s brand serves a means for customers to adapt their expectations. Customer experience also consists of this brand experience [21] and is evoked by subjective reactions from customers whenever exposed to brand-related attributes and communications [22]. The brand promise should reflect the organization’s brand values [20]. Smith [23] suggests a six-step approach to develop a consistent brand promise. An important activity throughout most of these steps, and unequivocally in the last step, is to continuously check the effects of the communicated brand to verify the delivery of its promise(s). Communication of the brand (promise) should not be restricted to the market but should also reach all employees of the organization, front office personnel in particular so that they are able to verify the delivery of this brand promise whenever in contact with customers [13, 24, 25]. A design principle in this building block for our tool-in-development should therefore state that the organization has to design (a) brand promise(s) that is(are) based on customer insights [23], which are communicated in both market and internal organization and repeatedly verified on delivery through customer touchpoints.

Service Design and Implementation An organization's processes, especially those processes that entail the involvement or participation of the customer like customer service, contact, relationship, and even handling, should be designed to maximally accommodate the customer's needs instead of guarding the efficiency of resources [1, 20, 26]. A continuous collection of and interpretation of customer data are needed for this, which makes service design and implementation a complex undertaking. Understanding customer experiences requires capturing rich information across all customer interactions with the service provider and even other service providers that support the overall customer activity. CEM builds upon multidisciplinary contributions in a way that systematizes this rich information and structures the holistic nature of customer experience [27]. In particular, manufacturing organizations that decide to follow the servitization path [28] should keep in mind that services are not to be regarded as add-ons for products but must be integrated with products to deliver customer-focused value to their core product offerings [29]. Technology can play an important part in the application of this building block [30]. Thus, a design principle in this context could read that organizations have to design and implement service processes based on rich customer data that is systematically and continuously collected in order to facilitate continuous improvement of the design process [20].

Customer Journey Application(s) The complete collection of touchpoints in the "journey" that a customer undertakes as a whole should be regarded [13, 29, 31]. Applying the customer journey approach entails that organizations have to identify these journeys, followed by a diagnosis of how it performs in each journey – also known as customer journey mapping – improvement of the performance and incorporation of the journey in operational processes (service design and implementation). To accomplish this, it is important to apply a cross-functional approach, where it is not only the front office that has to be involved [32]. We conclude with our third design principle where it concerns customer journeys that prescribes that for an effective CEM, the organization should identify its customer journeys, measure how its performance in CX is for the journeys, improve the performance, and incorporate the journey approach in standard operational processes.

Employee Management and Empowerment By now it should be very obvious that an organization's employees have an important role and responsibility in CEM [3, 13, 24, 25, 30]: delivering the brand promise, participating in service design and implementation, and improving and incorporating customer journey in their customer handling. Employees, particularly front office personnel like service and contact center employees, are the ones who have daily contacts with customers, one of the most important touchpoints in customer journeys. To become and stay aware of this responsibility, organizations should manage employees in a way in which they feel comfortable, without fear for failure or punishment, and empowered to do so [10, 33]. This requires a humanistic management approach from organizational leaders [34]. Organizational design and development aspects, like employee selection, training and development, rewarding, assessment, and employee satisfaction surveys including employee well-being such as physical, psychological, social, financial, spiritual, and environmental well-being measures, are important indicators for such humanistic management approach [35]. Our design principle should state that management should define, design, implement, and maintain a humanistic management approach in the organization where employees are empowered to optimally deliver customer experience.

Customers' Emotional Feedback In defining CX we have seen that besides functional, sensory, cognitive, and rational thoughts of customers, CX also consists of emotional, subjective feelings a customer gets or has during his interactions with the organization. It has also become evident that a customer's feedback, the evoked experience, has to be collected, analyzed, and interpreted in the context of the building blocks brand promise, service design, and customer journeys, while this feedback can also be of importance for the block employee empowerment. CX measurement, including emotional drives, needs, reactions, and expressions [20, 36, 37], thus forms important aspects of CEM. Yet, the measurement of emotions is difficult and full of fallacies because we tend to project our own emotions on what we experience from someone else [38] – empathy is needed to properly understand emotions in experiences [39]. This could be a reason that emotion measurement is hardly done by organizations [26]. A great opportunity to receive emotional feedback, however, is the input that organizations get from customer complaints and suggestions [36, 37]. This kind of feedback provides an organization learnings about the way customers think and feel about the organization, its brand, its products, and its interactions. When addressed and treated seriously, it gives one the possibility to optimize interactions [37]. And, when the receipt and interpretation of such complaints are not restricted to frontline personnel, but back-office personnel and managers are also involved, CX optimization can also affect back office and other processes, which do not take CX into account because of their invisibility for customers [36, 38]. We conclude with our fifth design principle that organizations need to set up a system, consisting of procedures and technology, that collects and interprets customers' emotions and which enables sharing of this feedback throughout the whole organization.

Five Separate Blocks, but Holistically Interconnected The additional literature review, in conjunction with the organizational interviews from step 3, resulted in the identification of five building blocks of an effective CEM – brand promise, service design and implementation, customer journey approach, employee management and empowerment, and customers' emotional feedback – that served to define five design principles for the CEM-Dashboard development. Although presented separately, it is obvious that all five building blocks are highly interrelated and interwoven. Good employee management is needed to deliver the correct brand promise, customer emotional feedback is essential to check the brand promise delivery, while service design is best conducted by using the customer journey approach. Customer journey mapping and improvement needs not only customer feedback but requires the involvement of cross-functional employees. The building blocks can therefore not be applied or implemented as separate actions in CEM but need to take a holistic approach. This implies that our tool-in-design should take this holistic view into account by addressing all five aspects in conjunction – and not to diagnose on only one or some aspects –, considering them of equal importance in CEM and to also interpret readings that result from application holistically. We will treat this insight as our design condition, an imperative for our design process and final design.

3.5 Step 5: Tool Design

As previously indicated we followed DSR guidelines [16] in designing our intended tool, the CEM-Dashboard. This entailed that for each building block – that resulted in design principles (see the previous section) – we made an inventory of the most important actions and elements that, together, when properly applied, result in an effective implementation of that CEM building block. Each action and element was then described as proposition using the CIMO-logic[1] which is usual in DSR. Design propositions describe what an organization should do (or do not) for an effective CEM implementation. Since the tool is intended to diagnose to what extent the organization has progressed with CEM and what its efforts have yielded, we chose to use the complete set of design propositions as a checklist to check to what extent each proposition has been completed. This was achieved by transforming each design proposition into one or more questions for the organization that measure the extent of implementation. Because of the requirement for a limited size for MCPC papers, we cannot present the obtained design propositions and underlying actions or elements (questions). An example of one of these design propositions and underlying questions is presented in Box 1.

[1]CIMO is an abbreviation of problem in context, intervention, generative mechanism(s), and outcome(s). CIMO propositions are formatted in these four aspects: To solve this problem in context (C), one should apply these interventions (I), which trigger these generative mechanisms (M) and therefore lead to these outcomes (O).

Box 1: Example of a Design Proposition and the Derived Questions for the CEM-Dashboard
Building Block 4: Employee Management and Empowerment

Design Proposition 4.3: In order to resolve management's problem of employees' contributions to a better CX (C), the manager has to acknowledge, discuss, and corroborate individual employees' performance on functional, social, and personal aspects in a systematic way (I) because this will increase employees' self-knowledge and self-esteem (M), which are needed to positively work on a better CX (O).

Questions:

Q57: Management acknowledges and discusses individual and team performance in teams on a periodical basis. Answers: Not assessed at all – Discussions are restricted to functional aspects, like number of customer contacts, average contact time, etc. – Discussions are restricted to social and personal aspects on an individual level, incidentally – Discussions are about both functional and personal aspects, on a team level, periodically – Team and individual performance are discussed periodically within teams.

Q58: How important are an employee's achievements and behavior for his/her assessment? Answers: Not at all; assessed, but with no consequences; slightly important; important; very important.

(a) Functional actions, like days present, time spent with customer, sales revenue, etc.?
(b) Social behavior, like empathy, communication, helpfulness, etc.?
(c) Personal skills, like conscientiousness, agreeableness, openness to experience, extraversion, neuroticism, etc.?

Because of their interrelationship, some different design principles yielded the similar or identical questions. These were reduced to unique questions, but taking into account that the question applies to more than one building block of CEM. Some of the questions can be answered by organizational representatives; some others – for example, questions regarding (emotional) effects – have to pose to the organization's customers to get an objective result. Answers to each question may vary between "not at all" – indicating that nothing has been done or achieved regarding this action or element – and "fully completed," indicating that the action or element is maximally implemented. We divided these answering possibilities for each question in five classes to reduce complexity in processing of results, to bypass the choice paradox [40], and to enable simple but effective benchmarking. In sum, our tool was shaped into a questionnaire, a very powerful and useful way to find out "what," "who," "when," "how," and "to what extent" to describe or explain phenomena in organizations in a structured way [41].

Surveys with predefined answering possibilities also facilitate analysis and interpretation using quantitative scores [42]. As for this design step, we chose to consider the five answering options belonging to an interval scale; each interval

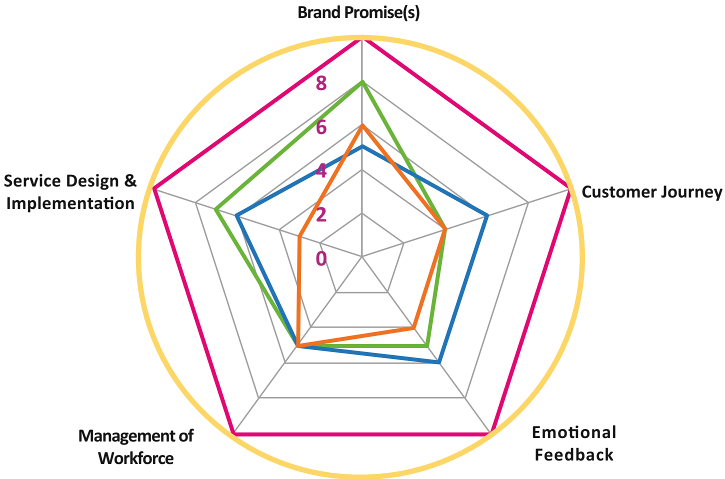

Fig. 1 Graphic representation of the results in a pentagon, example

represents 2.5 points, thus obtaining possible scores of 0, 2.5, 5, 7.5, and 10. The scores of all answers of a certain building block are summed and then divided by the number of questions of that building block. This will result in a score per building block, value between 0 and 10, indicating the degree in which this building block has been implemented effectively: 0 indicates that nothing has been done and accomplished in this building block, while a 10 represents the maximal possible achievement for the block. A graphic display in the shape of a pentagon, of which each corner stands for one of the five building block scores, denotes the holistic approach and interconnectivity of the building blocks in the diagnosis (see Fig. 1). The pentagon should be "in balance," meaning that all five scores have to be almost or fully equal. The CEM is "out of balance" when a building block score differs more than 1 point from another block. Improvements are designated by those actions and elements that have produced a score that differs more than 2 points from the average block score.

Application of the Tool in Practice Acting this way, we got two questionnaires or surveys, one for application within the organization and one for application among its customers. To facilitate an efficient distribution, handling, and processing, the survey is presented to respondents online. Within the organization it will be presented to manager(s) with responsibility for CEM, mainly because they are the ones who know the organization, its mission, and goals best [33]. To reduce the effects of the so-called overconfidence bias [43], the survey is also presented to three to ten (depending on organizational size) nonmanagerial employees of the organization. The selected respondents complete the survey and submit it. The organization's score is calculated by averaging the individual responses of both manager(s) and employees. This result, along with the pentagon, is reported to the organization. The difference between employees' score and managers' score is an indication of the overconfidence bias, which is also reported. When the pentagon is "out of balance," this is indicated, simultaneously suggesting improvement measures in terms of "too little is done regarding ... " in case of a low score or "too much emphasis exists on ... " in case of a high score.

In case of simultaneous application for more than one organization, for example, through intermediation of an umbrella organization, association, or union, for its member organizations, benchmarking of the results becomes possible. The organization's individual result can be compared to its peers or even the market as a whole. This can help to identify its strengths and weaknesses regarding specific business CEM aspects.

The Components of the CEM-Dashboard Tool The questionnaire intended to be surveyed within the organization consists of 72 questions that represent the accomplishments for the five building blocks. Seven (7) more questions are added to gather background data like organizational size, business sector, type of market, and so on. The questions are currently in Dutch and accessible on a Qualtrics platform (see Fig. 2) but can be transferred (upon request) to any other platform or translated in any other language.

The survey to be held among the organization's customers is intended to cross-check the organization's assertions on its CEM status and to measure the effects it has yielded. It is also in Dutch and online accessible via a Qualtrics platform. Questions are about what customers think and feel about the brand, its products and services, its appreciation, its employees, etc. It consists of 40 questions, including demographic questions. The questions correspond with the building blocks and are also stated in a way in which there are five answering options for respondents, resulting in a similar scoring structure as for the organizational survey. There are two variants that differ in question style and questions: a consumer survey for B2C organizations and a business customer survey for the B2B organizations.

After execution, the score and pentagon are calculated, for which an algorithm has been made. Reporting is done as described in the previous subsection and includes suggestions to improve individual CEM actions or elements and the "balance" of the program.

3.6 Step 6: Design Validation

DSR artifacts are not completed without validating that they work [16]. A very common way to validate a DSR artifact is a test in practice. So, we engaged with five organizations to achieve this. The organizations differ in size and industry and consisted of a financial service provider, a mobile service provider, a manufacturer (B2C), a city office, and charity organization. Each participant was intentionally left unaware of the other participants for benchmark purposes.

They completed the internal survey and facilitated the survey among their customers. They received the reports, including a benchmark represented by the average of all participants. Although the benchmark did not contain peers, it made

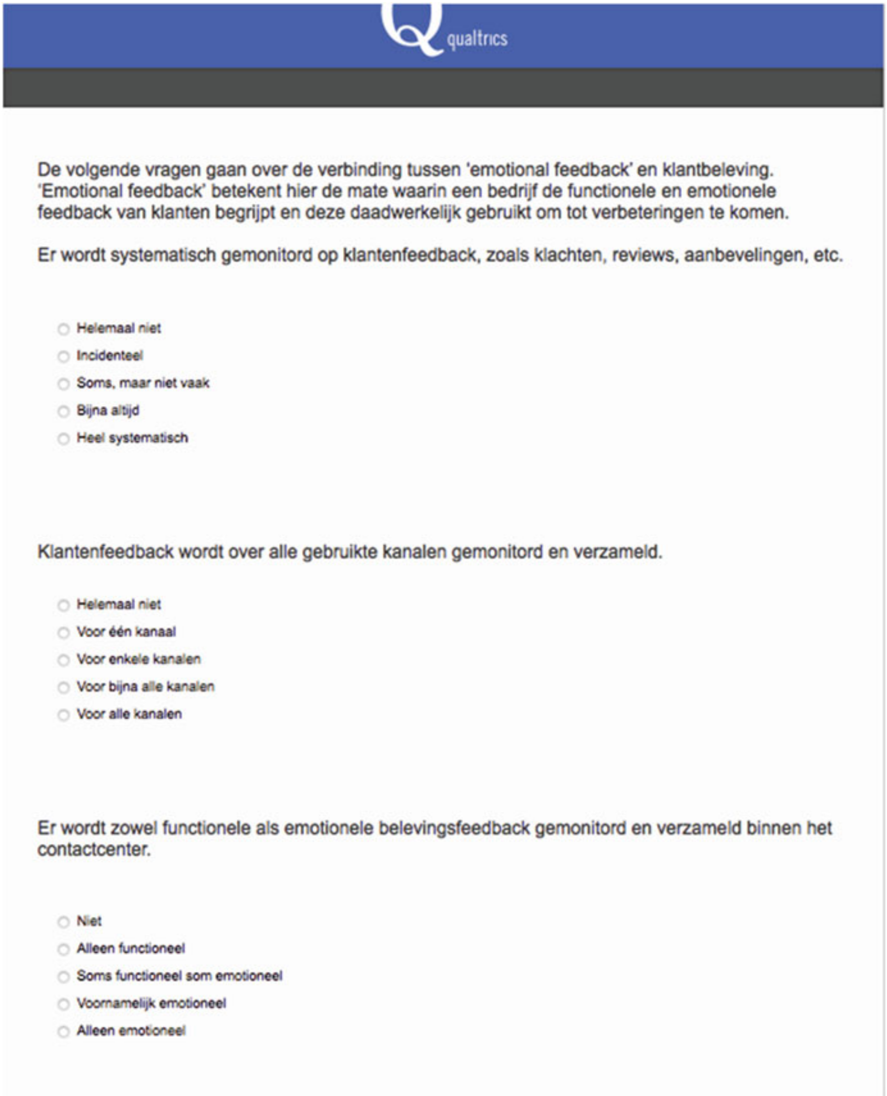

Fig. 2 Page example (in Dutch) from the organizational survey on Qualtrics platform

it possible to see how the benchmark works. They also were requested to complete an evaluation of the tool, consisting of the two surveys and a report. All participants reacted slightly positive to very positive in their evaluation, although also providing critique, which we will address in the discussion section. Some of these critical observations serve as input for the redesign of the CEM-Dashboard. This redesign is still in progress and has not been completed yet.

4 Discussion

In this section, we will address some of the critiques that have been expressed by the testing organizations and other observers that have also been requested to evaluate the usability of the CEM-Dashboard.

One first remark and warning concerns the "illusion of accuracy." Dictating and prescribing amounts of participants, assigning quantitative scores to answers, calculating averages, etc. might create the illusion that all such numbers have been thoroughly calculated, although this isn't the case. Many numbers are selected arbitrary, used only to facilitate *comparison:* comparison to other organizations (the benchmark) and comparison in time, when an organization decides to reuse the CEM-Dashboard to measure progress. This doesn't exclude the possibilities to develop exact numbers for participants, *weights* for scores, and a more exact algorithm to calculate the "balance," but these are actions that will take time and a large number of participants. We will look into such improvements, taking into account that previous measurements will have to be retrofitted according to the new standards.

Another critique was about the burden the tool can put on participating organization. They will have to appoint internal and external participants who are eligible and willing to participate in the surveys. We acknowledge that but do not have better alternatives, yet.

A third observation was made regarding the benchmark. The benchmark is regarded to be a useful asset as long as it remains anonymous, protecting the organization's intelligence from competitors. The benchmark therefore requires the participation of a substantial number of organizations. A single organization will not be the client of such an investigation. It is expected that orders to apply the tool will come from umbrella organizations, like associations, unions, societies, guilds, and such.

Finally, one can criticize the way the tool has been designed. This solution, to use questions, a distinct set of answer possibilities, quantitative scores, and an algorithm to calculate total scores, is part of the creative step, which is very common for DSR processes [16] and for which, however, several other possibilities exist. For example, another way to solve the problem could be to create an assessment team which will assess an organization's CEM progress upon request or as a certification requirement – for which a standard can be developed, comparable to ISO and other standards. Such an option is however very cumbersome and requires a long lead time. We made this choice because we think it is transparent and efficient, lowers the threshold to assess one's progress, and facilitates a benchmark.

In summary, we believe that, although there are other possibilities to do so and that the tool can be improved to be more accurate, we have developed a useful tool that gives an organization insight in its progress on CEM, its achievement (effects), and a benchmark in the market.

5 Conclusion

Customer experience management (CEM) is gaining in attention from companies in the latest years. More and more organizations take their first steps on the road to an excellent customer experience (CX) but are usually unaware of their progress, in particular when compared to their competitors. To fill this gap, we designed and developed a diagnostic and benchmark tool, the CEM-Dashboard, for such companies to determine their current position and improvement directions in their efforts to implement customer experience management in the company and its processes.

In six major steps, entailing both theoretical as practice research, we developed this tool that assesses one's progress in CEM. The tool consists of two surveys, one to be held in the organization, the other among its customers, and a report denoting its achievements on five major and mandatory aspects of CEM. It also has provisions for a benchmark by involving other (peer) organizations. The tool was tested and proved to be very helpful in closing the PDCA loop. Although there are several improvements suggested, which will be incorporated in a redesign – in progress – we believe to deliver the promise to give organizations insight in their CEM progress, the effects they have yielded, improvement actions and directions, and, finally, a benchmark.

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Product Configuration in the ETO and Capital Goods Industry: A Literature Review and Challenges

Bjørn Christensen and Thomas D. Brunoe

Abstract Product configurators are IT tools often used to enable choice navigation in mass customization environments, with the purpose of giving companies the ability to interact and deliver customized products to the customers. While product configurators have been widely adapted and investigated in the consumer industry, research on which challenges companies are facing in the ETO and capital goods industry, in regard to product configuration, is less extensive. Therefore, the objective of this paper is to identify challenges in applying product configuration for ETO and capital goods companies, as well as reviewing potential solutions in research, which can be applied to address these challenges. The findings show a gap between the solutions and challenges especially in the area of staging commitments of product characteristics, flexible management of alterations to the configuration design, and connecting decision criteria in product configuration with supply chain processes. The gap analysis lays the foundation for future research.

Keywords Product configuration · Supply chain · Complexity · ETO · Capital goods · Postponement · Staged order commitment · Phased literature review

1 Introduction

A product configuration consists of an artifact, a substance, information, or a service and is composed of an abstract representation of a product variant including a structure of entities and rules of how the entities and their properties can be combined. The task of the configuration is to combine predefined entities, may they be physical or nonphysical, and by inferring, selecting the variable properties, while obeying constrains and design interfaces [34]. A solution to the configuration task does not only show which components to use in the finished configuration but

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also how to connect them. The predefined set of components is maintained through product models, which describe all possible product variations and options available to the market [22].

Capital goods are any type of assets used for the production of income, consumer goods, or services and are generally considered as one-of-a-kind products with high complexity and requirements for substantial capital investment [43]. Examples of capital goods are buildings, trucks, airplanes, trains, wind turbines, elevators, etc. Supplying the market with capital goods is often managed using a project-based approach, where each customer delivery is designed, planned, manufactured, and delivered as a project [11], which involves a considerable amount of resources spent on, e.g., engineering and order processing following a sale. When the product is delivered and installed, the requirements to productivity and runtime must be as promised. This often requires an integrated solution with service providers, external stakeholder groups, and environmental infrastructure and disposal contractures. This type of product is often referred to as product-service systems (PSS) [32], which focuses on product operation and performance in the entire product life cycle.

In order to be competitive in the capital goods industry, companies engineer project-specific solutions in order to optimize the financial parameters for the customer. Such a supply setup is referred to as an engineer-to-order (ETO) supply chain [13] and is often found in the capital goods industry. Gosling et al. [13] presented a literature review, including multiple definitions of ETO supply environments that differ fundamentally in how design, engineering, and manufacturing are managed according to the customer order. For the purpose of this paper, ETO is defined as follows: An ETO supply setup operates in a project-based environment with project-specific demand, where existing design is modified to order and the customer order decoupling point is located at the design stage.

Product configuration, ETO supply environments, and capital goods have been subject to reviews in past research. These reviews are treating each topic separately with focus on configuring product platforms [48], issues and future research in product configuration [47], reference framework in product configuration [34], product family development [23], ETO supply chain strategies [13], managing design variety for capital goods [43], and configuring capital goods and service systems [37]. The reviews are to a large extent motivated by limited overview of a systematic collection of literature, consolidated within each area. The results of this are reviews focusing on the broad aspects of a topic, thereby internationally directing away from an application-specific domain.

This paper presents a literature review on distinct challenges that companies in the ETO and capital goods industry are facing in relation to product configuration. Based on the challenges, literature is reviewed to investigate a combined solution. The results are limited, and therefore a more detailed review of the individual challenges is needed. The review presented in this paper adapts an approach where the application domain is the premise and not a distinct topic: first, introducing the challenges in product configuration for ETO and capital goods; second, reviewing how literature has been dealing with the challenges in a consolidated solution; and third, breaking down the individual challenges to review them separately. Thus the research questions for this paper are:

RQ1: What are the main challenges in applying product configuration for complex engineered capital goods?
RQ2: Which solutions exist in research to address challenges in product configuration in the ETO and capital goods industry?

2 Research Method

The approach applied in this paper follows the method shown in Fig. 1. The method is based on a structured search strategy presented by Zins [49].

The applied method uses the five phases suggested by Zins, represented by the rows on the left side of Fig. 1. In order to adapt an application-specific approach, as described in Sect. 1, three search streams have been constructed for the purpose of this paper and are represented by the columns in the top of Fig. 1. Combining the search phases with the search streams creates a matrix format, where the streams work as a sequential process and the phases as an incremental process within each search stream. The method is used by first going through all the phases in the clarification search stream, then the synthesis stream, and lastly the analysis search stream. The outcome of the analysis search is a gap analysis presenting the

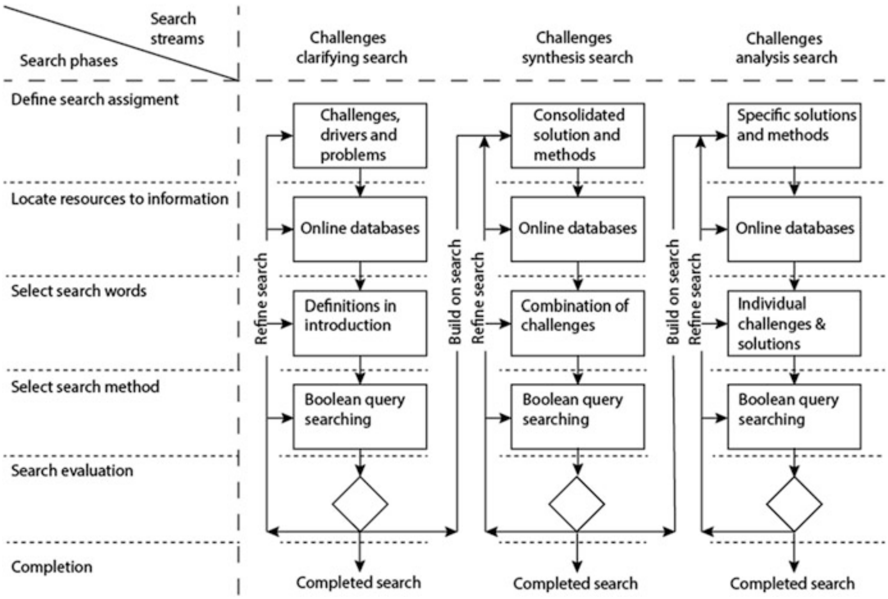

Fig. 1 Phased literature review model

Table 1 Search summary and keywords

Search stream	Papers after review	Keywords
Clarification search	27	Product config; ETO; Engineer to order; Capital Goods
Synthesis search	4	Order specification; Product specification; Process; Supply; Complex; Design; Stage; Multilevel; ETO; Engineer to order; Config; Long lead time; Tender; Bid; Customization; Variation
Analysis search	14	Postponement; Black box engineering; Product differentiation; Product platform; Product structure; Product modeling; Feature modeling; Config knowledge; Solution space; Modularization; Requirement management; Functionality management; Knowledge acquisition; Knowledge formalization; Parametric design

challenges, the corresponding authors, and the relationship between the two. The gap analysis shows to what extent the authors address each individual challenges, based on the criteria inferred from the challenges presented in Sect. 3.

The purpose of the clarifying search is to discover literature which describes the main challenges in applying product configuration for complex engineered capital goods. Based on the description of the challenges, the synthesis search acquires a top-down approach by designing a search including all the challenges and investigating potential solutions. The results are used to build the analysis search, which applies a bottom-up approach, by breaking down the combined solutions to the individual challenges and reviewing how research has addressed these individually. The keywords used in the search streams together with the resulting number of included papers are shown in Table 1 above.

The databases used in this literature review are Web of Science Core Collection, ProQuest, and Scopus. Boolean query search is applied to search the databases by structuring the keywords into Boolean blocks. After the Boolean search is completed, the identified papers are used in an associated browsing to obtain additional relevant papers. Evaluation of the search results leads to one of three conclusions as shown below and is based on the results' reliability, validity, relevance, and sufficiency [49].

1. Refining the search – Revising the search stream to modify and optimize the search results. Each search phase can be revisited after the evaluation.
2. Completing the search – The search result is satisfactory according to the assignment, and further investigation is not in scope for the research question.
3. Building on the search – The result of one search stream is used as input to the next. For example, the challenges derived in the clarification search stream are used to direct the search for solutions in the syntheses search stream.

The challenges and the corresponding solutions are reviewed in the flowing sections.

3 Challenges for Product Configuration in ETO and Capital Goods Industries

This section presents five main challenges in applying product configuration in the ETO and capital goods industry. The challenges are obtained by reviewing literature and support directing future research in the area of ETO product configuration.

3.1 Product Characteristics Are Gradually Determined Over Time

The need for product configuration in ETO companies shares similar requirements with other industries, where product configurators are used to manage the validity of the offered product and determine the product structure through a predefined set of rules [26]. Beside the common functionalities shared with other industries, capital goods companies operating in a tender-based environment, preparing bids for complex customized products, need to construct a competitive offer in order to win the tender round. However, the complexity of the bid becomes a challenging task for customer unique products because the product specification is usually not complete and/or violates basic contains and changes both during the preparation of the bid and handling of the project after an order has been committed [20, 27]. The bid preparation and execution is performed in stages by interdisciplinary business functions from initial customer contact to delivery [50]. In this type of environments, change to the product configuration naturally occurs as the order/project evolves and new standards, financial prerequisites, regulations, etc. change [31].

One key challenge in the gradual determination of product configuration is the exposure of what is referred to as “white spots.” White spots are incomplete product configurations, with an incomplete bill of material (BOM), subject to change and evolution over time [26]. The issue is that systems acting on the configured information need the derived material demand in order to execute production and purchasing planning, and “It is difficult to support the using of product features instead of material numbers or incomplete configurations in master production scheduling” [26].

3.2 Long Order Horizons Increase Product Demand Mix Uncertainties

Product mix uncertainties have a profound influence on configuring the order delivery date. Depending on the customization level in the capital goods industry, the delivery date can vary to a large extent – a high customization level with new design has a longer lead time and greater uncertainties than a low customization level with common parts, shorter lead times, and less uncertainties [39]. A common challenge for all customization levels is a long order horizon, which again results in uncertainties due to a volatile market and rapid technology updates. A long order horizon does not always result from shifting market conditions. Internal factors, such as poor coordination across business functions in the early design phase where requirements have to be interpreted, understood, designed, evaluated, and selected, can prolong development and sales offering if domain knowledge is poorly managed [3, 35]. In this regard, developing an estimated due date is a challenging task, when the product design is not yet configured, and can be costly for capital goods companies, which often are subject to liquidated damage in form of cost penalties for late deliveries [14].

Product customization and context uncertainties are contingency factors in early customer enquiry management as parameters in configuring order lead times and delivery dates [39].

3.3 Product Configurator Drives Supply Chain Activities

Product configurators drive multiple business processes in an ETO or design-to-order (DTO) supply environment [44]. These high-level processes are sales, design, production, and delivery/after sales [38]. In the sales process, an early engagement with the customer is often initiated for tendering purposes and requires a close collaboration throughout the value chain. Procurement and production deliver lead time and cost, R&D deliver conceptual design, and production and logistic verify propose product design according to operations and manufacturing footprint [44]. The design process can follow the product from selecting a conceptual design to specifying a unique BOM and operational routings [18]. Production processes in an ETO supply environment are characterized by a high product complexity, a very sensitive forecast of product mix and volume, and partly overlapping business activities such as engineering, sales, manufacturing, and installation [2]. For large-scale assembly products, relying heavily on environment integration and site installation, the configuration decision may consist of multiple system entities in the delivery process, such as final product integrator, service supplier, and end customer/consumer [29]. Product configuration needs to support a constrained application of supply chain management and manage the variety of work in ETO projects, where integrated networks of business processes are needed to ensure greater performance in tendering and design processes and thereby secure and increased order intake [19].

3.4 High Product Complexity and Comprehensive Product Variations

ETO and capital goods have complicated product structures, which require extensive design knowledge and different customized variants for different customers [45]. To customize such products, a combination of configuration and variant design must be applied in order to secure validity for design constraints, while still maintaining customer unique variants. The result of this configuration flexibility is an increase of part numbers and design complexity, which makes reasoning and sharing of knowledge more difficult [5]. Due to a complex product structure, unification of product variants through standardization of subsystems, modules, or components is comprehensive to design and represent in a knowledge base. Applying standardization in an ETO supply environment may lead solely to focusing on efficiency, while failing to balance efficiency, innovation, market requirement, and production capabilities [25]. Combining functions in modules through the concept of modularization and product platform management is located on a detailed level in the product structure, resulting in comprehensive product variations with few reuse of modules [12].

Complexity occurs in capital goods by a high number of customized components and a wide scope of required knowledge and skills involved in development, production, and product configuration. This complexity needs to be supported by intensive use of embedded product software and IT support systems for product design [1], such as simulation programs, computer-aided design, expert systems, etc. Products with these characteristics are sometimes referred to as complex product and systems (CoPS). Innovating CoPS requires supplier, regulators, and professional stakeholders to work together with customers in order to develop products and infrastructure design and environment integration. Delivery activities, including engineering and development, are often required to be performed simultaneously, which differs from mass produced commodity goods [21].

3.5 Solutions Outside the Configurable Solution Space Are Required to a Large Extent

Challenges in configuring customer unique products in an ETO and capital goods supply environments have been addressed in literature for the introduction of mass customization (MC) in ETO companies. Product configurators are commonly used to manage the solution space and to apply choice navigation as key enablers in becoming a successful mass customizer [10]. The crucial difference between ETO and MC in regard to product configuration is that the solution space is not predefined in an ETO supply environment; therefore, it may be difficult to apply regular approaches in constructing product platform structures, knowledge representation, and configuration solving [42].

The configuration process is a task of combining modules to construct a finished product variant; however, for ETO products, variety occurs internally in the modules where the structure of the combinations is more complex to manage, as opposed to mass customization. The variety is determined by the customer, which often demands characteristics of the product that are not possible to configure [36]. For this reason, the knowledge base is the main challenge in the transition from ETO to MC, because it is difficult to standardize the product to a degree that allows configuration [17]. These circumstances indicate that constructing a hybrid setup between ETO and MC in sales configuration may be a more suited solution for ETO companies moving toward mass customization [9].

4 Solutions for Product Configuration in the ETO Industry

Based on the challenges identified in the previous section, a second literature review is conducted and presented below for potential solutions.

4.1 Comprehensive Solutions Covering Multiple Challenges

The market needs to be supported in stepwise postponing the configuration specification for each characteristic until a decision is certain to be committed. This support is especially relevant when products outside the standard solution space are required. Zeng [46] introduces the concept of staged postponement of committing order specification in the commercial airplane industry. The purpose is to break down the order specification to product characteristics, enabling the customer to postpone the commitment of order attributes to different stages in the value chain. In traditional postponement, original equipment manufacturers (OEM), operating in a build-to-order (BTO) or configure-to-order (CTO) supply chain, are able to produce standard modules or platform components based on a forecast, storing them as semifinish goods, and when a customer order is committed customizing the final product variant [15]. Compared to traditional postponement, staged postponement gradually commits product features in a make-to-order (MTO) environment, enabling the customer to interact and adjust the order multiple times during the order delivery process.

Brunoe [4] addressed management of staged postponement in configuration and business processes for complex ETO maritime boilers, through the concept of a multilevel configuration system. Compared to traditional product configuration, it is possible to gradually specify the product over time and thereby make partly configured solutions. The concept also enables management of non-configurable components of an ETO product structure, by applying black box engineering as a method to customize parts of the finished product. A closer integration between the product structure, supply chain processes, and ETO operations is proposed by Kristianto et al. [26] through the application of system-level configuration, functional modularization, and black box engineering. The method uses a global BOM structure as a template in the system-level configurator, to infer the product configuration and enable a stepwise specification of characteristics in the development process for ETO products. Another way of achieving this integration is by applying an adaptable product platform with scalable flexibility and early adaptable architectural design, as suggested by Levandowski et al. [28]. The suggestion is a two-stage model used to manage the change in customer requirements over time. In the first stage, high-level information about the product architecture is decided. This relates to determining the overall technology covering multiple functional requirements. In the second stage, the designer uses a scalable configuration to propose a design solution, based on modules in an adaptable design architecture. The abovementioned references represent the main research activities in addressing the challenges. The next part of the solution review expands the literature scope in order to embrace research dealing with the individual challenges as well.

4.2 Specific Solutions Focusing on the Individual Challenges

Stepwise or staged postponement of product specification has been subject to research within the wider areas of delayed product differentiation, staged postponement of order commitments, and product configuration.

Czarnecki et al. [7] address staged/stepwise postponement through the concept of cardinality-based feature modeling. The concept introduces staged configuration by enabling a multilevel specification of feature models, where each stage has its own set of configuration choices, which the user needs to specify. The output of each stage results in a new feature model with related choices. Meerkamm [30] applies feature trees in creating a generic data model to integrate business processes and product configuration through a staged configuration and specification approach.

In order to account for ETO products when expressing configuration knowledge, Yujun et al. [45] use tabular layout of article characteristics (TLAC) to describe the context for nonstandard characteristics in connection with standard product programs, sharing similar attribute values across product platforms. Chavali et al. [5] use the process of designing components in a CAD system and referring the design to customer specifications, thereby enabling a reuse of information and inferring new configuration rules based on previously customer unique designs. This is performed when new configurations outside the standard solution space are required. Another method of expressing configuration knowledge in ETO is the use of rules. Combining TLAC and configuration rules in one data model has been suggested by Miaofen et al. [33]. The configuration rules are incorporated into the configurable feature tree and are controlling the main specification process. The outcome of the configuration task is multiple modules to make a finished variant. Each product module is described by a thing characteristic table (TCT), which relationship with other TCT, define the design relationships. With a clear defined design relationship, designers can reduce the development lead time for nonstandard configurations by, instead of modeling a predefined set of entities, available to the configuration task, using black box engineering to redefine the product specification process into a way of communicating high-level requirements for product functionality and performance [24]. Black box configuration adapts black box engineering as a method to customize parts of the finish product by configuring the interfaces between the black boxes and the remaining configuration, thus leaving out the internal structure of the component [40].

Integrating the customer with the design process in stages has been suggested by Dou et al. [8]. An interactive genetic algorithm (IAG) allows the user to perform collaborative product design with the designer through an interactive user interface and in stages evaluate the product. Based on similar user trends, the algorithm suggests characteristics best suited for the customer for each individual design stage. Designing or developing in stages addresses the numerous changes in product specification and requirements. Chen et al. [6] developed an IT program to manage how multiple engineering changes concurrently influence the product model in a configuration process, which results in a product variant design outside the standard solutions space. The program is structured through an interlinkage of product attributes, which uses the capabilities of object-oriented programing to determine the change relationships.

Brière-Côté et al. [3] apply and develop the adaptive generic product structure (AGPS) in an ETO supply environment in order to enable a systematic aggregation of product variants as they mature through the sales process. A clear categorization of severity for unordinary product specifications assists in controlling the modeling of the product family and how it impacts supply chain processes, especially during the sales phase. Pandit et al. [35] use ontology as a typography to model the information flow between organizations, processes, and product design for nonstandard customized products. These entities need to be committed to the ontology in order to secure system integration in the entire value chain, between product engineering and business processes. The activities within the ETO configuration processes have been investigated by Willner et al. [44]. The activities are categorized in functional areas and business processes, in a matrix format, describing tasks, input data, software tools, and benefits for each combination of the two. Schönsleben [38] made the connection between the customer and company processes when nonstandard or customized product configuration is required. The method used to accomplish this is modularization, parametric product modeling, and dummy positions in bill of materials.

To manage the configuration complexity of the product, Haug [16] investigates modeling techniques for knowledge acquisition from engineering domain experts to knowledge engineers and formalizing that knowledge into a product configurator. Tidstam [41] has further investigated the formalization in the vehicle industry by applying configuration rules for knowledge representation.

4.3 Solution Review Summary

The above solution review is evaluated based on the five below criteria, inferred from the challenges presented in Sect. 3.

1. It is possible to stage product configuration and make stepwise commitment of product specification.
2. The product configuration setup enables the user to change requirements frequently, possibly imposing engineering changes while still having a reliable configuration output both to the customer and to internal business processes.
3. The information flow connects and interlinks the decisions made in product configuration with supply chain processes.
4. The product configurator setup supports the management of a complex product structure and complicated engineering knowledge.
5. The configuration process enables the configuration of a product design or engineering structure when a request outside the standard solution space is requested.

The result of the evaluation is summarized in Fig. 2.

The challenges are listed at the left-hand side of Fig. 2 with corresponding references and, at the top, authors proposing solutions to the challenges. On the right-hand side, the sum of the evaluation per challenge is calculated and at the bottom per author. In the middle, the evaluation of how the authors address each challenge is presented. A fully filled circle indicates a high degree of fulfillment and a non-filled circle indicates a low degree of fulfillment. The degree to which the reviewed authors satisfy these criteria is subjectively evaluated based on the context of each reviewed paper.

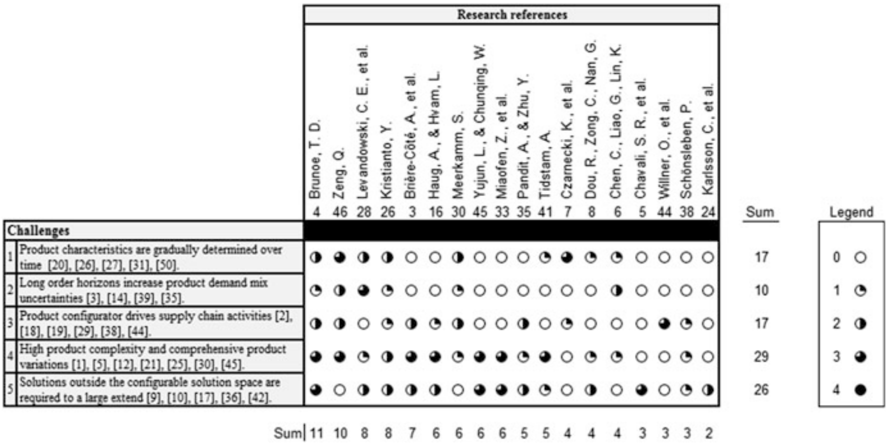

Fig. 2 Gap analysis between challenges and research solutions

4.4 Research Gap

The gap analysis focus on three types of gaps, namely, how extensively has a challenge been subject to research, to what extent has the combination of the challenges been addressed in a research contribution (by an author), and what is the focus pattern of the research treating the challenges. The purpose is to direct future research within the area of product configuration in the ETO and capital goods industry. With reference to Fig. 2, the gap analysis shows that challenges 4 and 5 have been treated relatively more in research, with a larger diversity of authors, compared to the rest. Challenges 1 and 3 have a different research profiles. The two challenges have only been treated to a limited extent in research, often not by the same author, which indicate a gap in clarifying the mutual impact between the two. Challenge 2 has not been the main topic of any of the presented research contributions and is often treated in connection with challenge 1.

The pattern of previous research indicates a limited connection between research in gradually specifying product configuration over long order horizons and supply chain processes with nonstandard product solutions. Even though research contributions have been provided for the challenges, the connection between them has only to a limited extent been clearly treated. Thus, the gaps and future research themes are:

- Combining a staged product specification approach with the management of product knowledge complexity and requests for solutions outside the standard solution space
- Connecting a gradual decision process in product configuration, during long order horizons, with supply chain activities
- Designing and managing complex ETO knowledge engineering in product configuration

5 Conclusion

The conclusion will answer the research questions developed by discussing and defining product configuration, capital goods, and ETO products, together with suggesting a future research agenda.

RQ1: What are the main challenges in applying product configuration for complex engineered capital goods?
Based on a literature review, five main challenges were found in applying product configuration for engineer-to-order capital goods. The capital goods and ETO companies operate within an environment where product characteristics are gradually determined over time, the product configurator drives the supply chain, long order horizons increase product mix uncertainties, high product complexity and extensive variations complicate solution space management, and customer unique products are often required by the market.

Rapid and frequent technology updates and shifting market conditions in the ETO and capital goods industry impose uncertainties in the product specification process. The market typically operates in a tender-based environment and is not able to make a fully specified configuration in the early stages of a sales opportunity. A main contributor to this uncertainty is a long order horizon, which results in frequent alterations to the configuration as new technologies emerge and external priorities and considerations change. In these very volatile conditions, the product is often characterized by high complexity with multiple designs, market, and offerings constraints. Further, adding to the complexity of the product, customers often request products outside the standard solution space in order to improve their business case. This triggers a series of design events and logistics engineering, which prolong the order horizon, increase specification uncertainties and add to the product complexity.

RQ2: Which solutions exist in research to address challenges in product configuration in the ETO and capital goods industry?
Based on the challenges, solutions in research were reviewed and evaluated from five main criteria, namely, staging product configuration, managing frequent engineering changes through configuration, relationship between decisions in product configuration and supply chain processes, support of complicated engineering knowledge, and configuration management of ETO products. The review found 4 main research contributions broadly covering the majority of the challenges and 14 less covering contributions focusing on solutions to parts of the challenges. The main topic of the solutions is to adapt a stage approach to product configuration, thereby postponing the commitment of product characteristics in different stages to support value chain activities as they are being executed. Integrating this concept with knowledge representation of product structures and design constrains for products with engineering requirements after sales has been suggested by the use of black box engineering and adaptable product platforms.

The research gap infers the future research agenda. (1) Product configuration is, as the word implies, the activities of configuring a product. Consequently, product configurators are not constructed with the aim of accounting for the relationships with the supply chain, both in regard to the decisions made by the use of the configurator and the development of it. It would be interesting to investigate how the configuration processes connect and impact the value chain in order to enable a holistic supply chain configuration. (2) In the ETO and capital goods industry, there is a need for postponing the determination of product characteristics due to specification uncertainties. It would therefore be valuable to explore how to gradually commit configurable product structures to be applied in value chain processes instead of over-specifying a product variant up-front and changing the requirements as the uncertainties diminish. (3) Accounting for uncertainties in product configuration together with optimization techniques to infer the most suitable configuration for each customer is a new and highly relevant topic to be investigated. Incorporating optimization algorithms, simulations, heuristics, and application uncertainties with product configuration would support and improve business cases transparency. (4) Final point on the research agenda is the configurator's ability to support configuring customized products such that unforeseen customer requirements can be fulfilled. Here, there is a need to investigate product configurators dealing with new component or function development and how product structure modeling, knowledge bases, and reasoning logic can support that.

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The Individualization of Mass Customization: Exploring the Value of Individual Thinking Style Through Consumer Neuroscience

Frances Turner

Abstract Neuromarketing is looked upon by some with suspicion, others with enthusiasm: it is seen either as a dastardly way of getting inside our heads to make us buy what we do not need or a potentially better means to glean more accurate consumer insights to guide design and production of goods, services, and experiences leading to commercial success. Can brain science reveal the nature of individual thinking style to help the consumer collaborate so effectively with the mass customization (MC) provider such that she really gets exactly what she wants or needs? Could deeper knowledge by the consumer of her own neural processes empower her to assist the MC provider in elevating her perception of value of the customer experience? If an individual's thinking style is innately unique and situation or context specific, then studying the individual's perception of the consumer experience via exploration of factors related to her inimitable cognitive processing could help individuals gain, and practitioners and scholars provide, further insights into enhancing the relational value of MC. This paper is an initial exploration of how consumer neuroscience might be useful to the consumer and firm to further individualize and enrich the consumer's perception of value of the mass customization experience.

Keywords Mass customization · Consumer experience · Individual thinking style · Loyalty · Co-design · Co-creation · Personalization · Individualization · Consumer behavior · Consumer neuroscience · Neuromarketing

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1 Introduction

In their empirical study, Turner and Merle [57] found individual thinking style enhances the individual's perceived experiential value of the online MC consumer experience. These findings help discern factors related to the uniqueness of cognitive processes that could inform consumers, practitioners, and scholars of ways to increase loyalty to MC programs. This paper explores ways neuroscience can reveal deeper insights into individual thinking style and how such information can be used to further enrich the relational value of mass customization.

Some scholars have defined consumer neuroscience and neuromarketing separately and others in a kind of combinatory manner. Lee et al. [35] describe both terms as "the application of neuroscientific methods to analyze and understand human behaviour in relation to markets and marketing exchanges." Hubert and Kenning [28] define consumer neuroscience as a "research approach ... compris[ing a] ... scientific proceeding," whereas "neuromarketing designates the application of the findings from consumer neuroscience within the scope of managerial practice." Fisher et al. [20] assert the field is "marketing designed on the basis of neuroscience research." For the purposes of this discussion, we will use the terms interchangeably as did Morin [39]: "Neuromarketing is [a] field that bridges the study of consumer behavior with neuroscience."

If through neuroscientific methods a provider gains access to information about the neural activity evoked in a consumer's brain, neuromarketing to target offerings to the individual may be a welcome and effective tool in securing consumer loyalty. On the other hand, a consumer's access to information about her own neural responses could guide her in searching for providers who cater best to her wants and value perceptions. In helping her gain deeper awareness of her thinking style, consumer neuroscience could assist the individual and the MC firm in co-designing more optimal MC consumer experiences.

2 That Holy Grail, Loyalty

The essence of mass customization is the collaboration between consumer and firm, with the latter providing a design template, options of features, and tools the consumer uses to select and devise an offering uniquely specific to her preferences. This integration of the customer in MC is "the main origin of customer loyalty" [19]. With loyalty the ultimate goal of any firm, and e-commerce providers especially vulnerable to churn due to the ease with which online customers can change providers [1, 5, 42], an individual aware of her neural proclivities could use such knowledge to switch easily between providers of online experiences with one simple click. Information is power, and this increased consumer empowerment could further imperil the long-term relationship with the firm. If neuromarketing is applied in a consumer-centric manner with the good of the individual paramount, the firm would use and mine insights from this data to ensure consistently superb consumer experiences. On the other hand, if the customer's discernment of her tendency to use decision heuristics most natural to her allows her to identify ideal providers who she believes will offer her exactly what she wants or needs, then neuromarketing might be transformative for the individual (Pine and Gilmore 2011) and result in a longer standing relationship between her and the firm. Application of consumer neuroscience as described could help the individual and motivate the company to render better experiences, resulting in collaboration that creates offerings that yield greater relational value, the source of the firm's sustained competitive advantage.

Multidimensional theories that describe the essence of loyalty acknowledge behavioral and attitudinal characteristics [53, 60]. Loyalty is not simply the result of actions represented by repeated transactions but springs from the consumer's attitudinal and affective disposition occurring and developing over time through positive, collaborative experiences between the customer and the firm [29, 42]. El-Adly and Eid [13] confirmed the relationship of the consumer's perceived retail mall experience on satisfaction and loyalty. Based upon scholarship on experiential values and relational outcomes in MC, e-loyalty, and e-retailing [10, 11, 19, 18, 36, 47, 49] Turner and Merle [57] found the consumer's perceived values of control, enjoyment, and complexity influence the online MC co-design experience's impact on satisfaction of and loyalty intentions to the MC program, as well as did psychological ownership [10, 55]. Attitudinal loyalty is comprised of emotion and cognition, so if these are essential precursors to loyalty, then "current advancements in neurological and psychological testing technologies [will allow] researchers to measure loyalty more accurately than ever before" [60]. Emotional loyalty is generated by experiences with the firm that elicits strong, positive emotions from the consumer. Cognitive loyalty results from the brain's affective processing in which the individual develops a strong attachment to the object of the affect, forging a psychological connection to that object. This leads to the formation of "positive thoughts and beliefs" about the next buying experience with the firm. These two characteristics of loyalty work cooperatively and simultaneously [60].

3 Individual Thinking Style and the MC Consumer Experience

Scholars suggested the MC field delve deeper into research on individual differences. Franke et al. (2010) advocated exploration of situational and contextual aspects, among them those related to individual or personal characteristics of consumers. In their study on utility and complexity, Dellaert and Stremersch (2005) noted the necessity of "more detailed research ... at the level of consumer information processing." Utilizing Novak and Hoffman's [41] scales for measuring situation-specific thinking style (SSTS), Turner and Merle [57] demonstrated individual thinking style influences the consumer's perception of the value of the co-design experience in online MC.

In cognitive psychology and neuroscience, several major categories of thinking style have evolved, among them dual cognition, or the idea that human beings utilize parallel planes of thought in daily life (for an interesting meta-analysis, see [43]). Epstein [15–17] developed cognitive-experiential theory (CET) describing rational and affective cognition as distinct, co-existent learning systems utilized daily by individuals and noting "the extent to which [people] employ each should be an important personality variable" [16]. Using the CET scale as a model, Novak and Hoffman [41] developed SSTS as a "process measure" of performance and attitudinal cognitive tendencies or prevalence in specific situations. The SSTS scale identifies when rational or experiential thinking style is employed, affording researchers the ability to categorize a given task or situation as inherently analytical or experiential. Empirical evidence supports both experiential and rational thinking styles as enhancing the consumer's perceived experiential valued of collaborative design, particularly in mass customization [41, 55, 57]. Novak and Hoffman [41] found "significant positive correlation" between participants' use of their experiential (rational) thinking style to attitudes toward engaging in experiential (rational) activities, concluding, "People hold a more favorable attitude toward an activity when their thinking style fits the activity" [41]. Turner and Merle [57] found that during the MC co-design experience, experiential thinking increases the consumer's perception of control while decreasing that of complexity, whereas rational thinking increases perceived complexity, enjoyment [57], and psychological ownership [55]. Novak and Hoffman [41] suggested future research might reveal both experiential and rational thinking styles as exerting simultaneous positive influences on task outcomes. Song and Zinkhan [52] determined "as the level of message personalization increases, interactivity perceptions [of a website] are enhanced." Studies on the design of ambient online shopping environments [61] and on web morphing [27, 58] reached similar conclusions to those of Novak and Hoffman [41]. Morphing websites "automatically match ... the basic look and feel of a website, not just the content, to cognitive styles" [27]. In real time, bank and telecommunications websites morphed or changed in "response" to the unique communication styles of individual users, leading them through tailored e-commerce experiences [27, 58]. These studies' findings complement Novak and Hoffman's [41] observations, underscoring the importance of designing and developing offerings with elements especially congruent to individual thinking styles [55, 57].

4 Individual Differences and Thinking Style in Neuroscience

Initially, many neuroscientists held firm to the discovery that every human brain shows similar activity in the same regions of the brain. "[M]ainstream cognitive psychology and neuroscience have been primarily focused on the capacities and constraints all human minds have in common, and until recently barely considered individual differences in cognition" [32]. Researchers have demonstrated these similarities are distinct from person to person [7, 30, 37]. At their depth, neural activities are disparate, idiosyncratic, and unique, due to individual differences in cognitive processing, personality, physiology, perception, stimuli, and other situational influences [30, 37]. Unique distinctions underlying similarity in brain area activity are the sources of differences in cognitive processing style, described as finer measures of individual differences including brain "white matter integrity" – the efficacy of the 40–50% of the brain comprised of the connections between cells enabling communication between neurons – as well as personality and other individual and situation specific factors [37]. Brain imaging has shown that where activity appeared similar for certain brain regions in individuals performing the same task and achieving the same performance results, differences in thinking style generated "highly distinct patterns" of cognitive processes [37].

One might compare these distinctions using the concept of utility. While utility should be defined in terms of its context [21], generally, it is conceived as the want-satisfying power of an offering. Bentham [2] wrote, "By utility is meant that property in any object, whereby it tends to produce benefit, advantage, pleasure, good, or happiness." These benefits have basis in emotion and logic, and both work together to generate value in the individual's mind. Indeed, the variety of concepts of utility – such as predicted utility, remembered utility, experienced utility, decision utility [6, 38] – are distinct from one another, but related [6]. We can think of the assortment of types of utility as proxies for the variety of individual perceptions of value, with the twist that each perception has something that makes it unique – if even infinitesimally so – from another human being's perceived utility. In testing these various utilities, neuroimaging methods revealed activity in "brain regions active when people calculate value ... [with] ... considerable overlap in the neural machinery and cognitive processes" [38].

Neuroscience scholars have found analytical processing in the brain must involve affective processing in combination with analytical cognition [4, 48, 60]. Fugate [22] noted these areas and processes include large-scale regions "where logic resides" and the "system [considered] the seat of emotional response." Immediate rewards "prevail" over later, more rational ones, and when the more emotional ones are satisfied, the firm can proceed to appeal to the consumer's logic and reasoning [22]. Therefore, to the firm that recognizes this order, neuroimaging affords an enormous opportunity to identify market offerings to the consumer at the appropriate time [22]. However, strong negative reactions to stimuli will override the brain regions of logic. For example, Fugate [22] rendered what might be a lesson in the neural source of the consumer's perceived relational value, loyalty: the perception of unfairness destroys a relationship and makes any bond extremely difficult to restore because the brain's "neural wiring from its early formative period ... protects it from known dangers" so it continues to "repeat safe behaviors" [22]. Conversely, an individual's perception of great trust stimulates hormonal activity in areas of the brain resulting in the sense of pleasure or "emotional satisfaction" [22].

While determining the finer, underlying neural processes in individual thinking style may prove challenging presently, studies by cognitive psychologists and cognitive neuroscientists suggest helping individuals understand the nature and workings of their thinking styles would "benefit applied fields" [32] providing positive outcomes for the individuals, organizations and all involved [32, 43]. "[C]ognitive style has a place in, and should be integrated into, mainstream cognitive psychology and neuroscience ... aid[ing] research and the application ... across different disciplines and ... lead[ing] to new insights into individual differences in cognitive functioning more generally ... [and] understanding individual differences in cognition more broadly" [32]. Attentiveness to thinking style is viable for teachers to help students achieve more positive and effective experiences and outcomes in education [32]. The same can be applied to promotional communications, business, interpersonal relationships, and other areas [43]. Situation- and context-specific factors strongly influence the results of individual thinking in decision-making [43]. For positive outcomes "compatibility between thinking style and task characteristics determines the optimal processing mode for each decision situation. Messages that aim to encourage desired behaviors could be framed in a way that triggers the desired processing mode. Stronger relationships tended to occur when characteristics of the decision task or decision process matched the theoretical strengths of the thinking style" [43]. Kenning and Plassmann [30] proffered that consumer neuroscience offered "insights into the neural underpinnings of advertising processing, choice behavior, and brand preference processing." Given the complexity of its "underlying mechanisms of consumer behavior," the brain must select and use decision processes that differ and "recruit" a variety of areas throughout the entire brain [30]. These processes vary by "the stimuli, the context, and the physiological state of the subject" [30]. Miller et al. [37] agree, noting "any inference that can be made about an individual based on their pattern of brain activity must take into consideration the multiple factors that can contribute to the variations in that activity."

5 Individualization and Mass Customization: Like 23andMe?

At its essence, mass customization is individualization [25], as the co-design process results in outcomes unique to each consumer with the final offering delivered via cost-efficient, flexible mass-production processes [9, 24, 26, 31, 44, 54]. Body or body part scans are used to produce fashion items, glasses, and statuettes specific to consumers' body dimensions. Ghandi et al. [23] described personalized food and meals produced to meet nutritional needs and vitamin therapies customized to an individual's DNA. Individualization is not new. Lesko and Schmidt [34] note, "Individualization of drug therapy described as tailoring drug selection and drug dosing to a given patient, has been an objective of physicians and other healthcare providers for centuries ... to optimize the efficacy of a drug, minimize its toxicity, or both." The value of individualized approaches exists in applications such as ovarian stimulation and medical literature [14, 33, 34]. Neuroscientific research exposes similarities observed in brain functions and areas, which neural imaging techniques only scratch the surface of revelation: underneath these similarities or generalized neurofeedback are extraordinarily unique combinations of processes, each distinct to every individual's brain [3, 7, 30, 37, 38, 51]. Every brain is and acts differently requiring "a rich repertoire of methods for characterising subtle functional differences between individual brains and minds" [7]. Neuroscience must "honour the idiosyncrasies that are at the heart of how the individual brain gives rise to the individual mind, endowing a complex world with a unique meaning and producing successful behavior" [7].

As digital technology hastens the growth and future evolution of MC, the on-demand economy expands, and customer-centricity and consumer experience become deciding factors in achieving and sustaining competitive advantage, consumers will have more access to providers to get exactly what they want, exactly when they want it [45]. What might lie on the horizon for how the consumer can optimize her options for providers delivering unique value in her ideal offering? Maybe we should look to direct-to-consumer (DTC) genetic testing companies, such as the biotechnology firm, 23andMe. In the USA, the National Institutes of Health (NIH) cautions, "Direct-to-consumer genetic testing refers to genetic tests that are marketed directly to consumers via television, print advertisements, or the Internet ... provid[ing] access to a person's genetic information without necessarily involving" doctors, healthcare professionals, or counselors versed in the clinical use of the tests' information [40]. The NIH's Genetic Home Reference webpage features statements from several medical associations advising consumers to consult professionals before making conclusions about DNA information yielded by these tests. Ethical, privacy, standards, and other issues abound, particularly around consumers' use of information to diagnose the potential for health problems on their own, though much more research is necessary on all sides of these matters [40].

Genetic testing provides a person interesting data and opportunities to marvel at one's lineage and origins; and that data is in the individual's hands to explore and use in ways she sees fit. Now, consider development of an offering similar to DTC genetic testing in the realm of neuromarketing. The field of neuroscience pursues research and clinical applications to change behavior, like smoking, overeating, poor financial decision-making, that improves human wellbeing and quality of life. It aims to alleviate serious conditions like Parkinson's and Alzheimer's diseases, as well as advance marketing research and consumer behavior data, some of which is used to influence purchase. Learning more about the nature of one's thinking style – not only from psychological testing but from neural processing measures – could be of relational value to the consumer and MC firm. Aside from helping the firm better segment and target its markets, could the value of neuromarketing be its ability to provide information to the individual who can choose to use the knowledge to better select providers of offerings important to her? Given what we know to date about thinking style and its value in rendering better perceptions of experiential value, i.e., control, enjoyment, complexity, and psychological ownership [55, 57], consumer neuroscience could serve to enhance further the individualization of MC and relational value of the MC experience. Today the consumer can search for and discover many things about her unique self whether she fills a test tube with saliva or a cheek swab for information on her DNA and utilize the Internet of Things (IoT) via wearables and smart devices that track her location, count her steps, monitor her sleep, and offer various other types of biofeedback. Technological and scientific advances and methodologies such as neural networks and atlases, big data, machine learning, and artificial intelligence [8, 12, 50, 62] put us on the road to new, constant, and staggering life-changing developments and commercial applications. The capacity to delve deeper into the neural bases of individual thinking styles would put us on the road to "neuro-individualization" and "neuro-mass customization."

6 Limitations

As noted in this paper, technology for individualization exists in areas such as medicine and biometrics, and is commercialized in offerings like wearables and direct-to-consumer genetic tests. However, the concept suggesting development of neuromarketing offerings for consumers to use to assess their own thinking styles may be impractical today or technologically premature, in spite of the plethora of innovation and scientific advances. Cognitive psychologists and cognitive neuroscientists [32, 43] caution that even with the advancements of twenty-first-century brain science, there is much neuroscience has yet to uncover about individual differences in thinking style regarding distinctively unique neural underpinnings. Further, this paper does not consider demographic, inter-individual or cultural differences in thinking styles [59]. Lastly, while mentioned briefly, this discourse does not attempt to delve into ethical and other societal considerations, matters which would surely arise out of marketing a consumer offering for self-neuroscientific assessments.

7 Theoretical and Managerial Implications

Via neuroscience, the theoretical lens of individual thinking style can illuminate the depth of the dimensions of consumer loyalty in MC. To our knowledge, there is little to no literature on the neural underpinnings of individual thinking style as applied to the consumer's perception of value of the MC customization experience and loyalty or any other relational value. Also, there appear to be no research studies on using neuroscience to inform or enhance the design of the MC experience by providers or provide consumers the capacity to learn about engaging their chosen levels of thinking style to enhance the co-design process.

Regarding managerial practice, we believe the MC firm will be able to use neuroscientific tools to better engage and serve consumers, like those suggested for use in education and business [32, 43]. Firms might develop commercially viable tools similar to DTC genetic tests that individuals use to measure their own thinking styles and identify appropriate use situations that render optimal experiential value. Turner and Merle [57] suggested managers employ measures, like Novak and Hoffman's [41] SSTS scale, to inform design of MC programs to enhance the perceived value of the MC experience: structuring MC toolkits with co-design mechanisms created to complement and evoke individual thinking styles during the MC process could be part of the MC firm's strategies and tactics in marketing more effective co-design programs [57]. This paper extends that recommendation further, suggesting firms apply neuromarketing tools to the design of MC programs and develop offerings consumers can use to capture insights on their thinking styles that empower them to reap the best in relational value from mass customization. Either or both strategies should accomplish the ultimate goal of achieving enduring loyalty between the MC firm and the consumer.

8 Conclusions and Future Research

Neuromarketing and neuroscientific methods may be able to play an important part in optimizing the MC consumer experience at the individual level given the field's revelations that fine, inimitable distinctions in every person's cognition live under the surface of human similarities in brain activity and act to form each individual's perception of her wants and needs. Capturing both the challenge and prospect of neuromarketing, and individualization of MC and other fields, Miller et al. [37] emphasize the "systematic nature of variations in brain activity between individuals offers a unique opportunity ... to use neuroscience to understand unique aspects of the individual mind." The intangible, perishable, and unstandardized nature of service delivery is rife for digging deeper into understanding the consumer's value subjectivity. If thinking style proclivity leads to billions of distinct cognitive assessments of individual value perceptions and bases of desire for uniqueness, neuromarketing could be a "prophet for profit" [56], motivating the firm to identify a plethora of consumer-centric, value-capture insights, and helping the consumer better recognize and select ideal providers of individualized offerings, those who best create and render her unique, distinctive value.

Neuroscience confirms the importance of recognizing and appealing to individual thinking style, as well as understanding that situation-specific and a host of other variable factors contribute to an individual's unique perception of stimuli, whether positive or negative. It supports the firm's creation of consumer experiences and individualized custom offerings that appeal to, and are congruent with, a consumer's cognitive inclinations. Thus begins a conversation on how consumer neuroscience of individual thinking style can enhance the consumer experience in mass customization and other sectors. Underlying such discovery is the hope that as individuals and organizations work symbiotically to improve the human experience, together we can transform ourselves, one another, and society for the better.

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User Interface Modifications in Established Product Configurators

Paul Blazek, Clarissa Streichsbier, Martina Partl, and Lars Skjelstad

Abstract The evaluation of the gathered data in the Configurator Database, the biggest collection of web-based product configurators, shows dynamic patterns of growth and decline in product configurator offerings in the last years. While customizable products of all product groups and industries disappear from the market and others are newly added, there are quite a number of established customizable product offerings. This paper researches how the product configurator user interfaces of these successful products undergo modifications when compared over time.

Keywords Product configurator · User interface · Interaction · Mass customization

1 Introduction

Mass customization, derived from the combination of the contradictory terms "mass production" and "customization," is possible for nearly every product. This concept allows a company to respond to customer needs and demands. The communication between company and customer is a crucial requirement in a mass customization process, which is realized by a web-based customization tool, a so-called configurator. This application enables users to design their own, individual products exactly matching their needs [1]. The interfaces and features of these tools can vary, also with respect to how well they represent the total solution space [2]. Nevertheless, mostly a well-defined configuration space is provided, which defines possible configuration options [1]. By shifting the time-consuming tasks of the

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identification process to the customers themselves, configurators are one of the efficiency drivers for the mass customization concept [3]. But when moving the responsibility of creating an individualized product to customers, companies have to face that certain requirements to support and guide the customer in the process without creating confusion are necessary [1].

So it is comprehensible that the success of a configuration system doesn't only rely on technological capabilities. A lot of research underlines the importance of an appropriate user interface that supports the understanding of the configuration options and process, visualizes the product in an expected way, guides the user, creates positive emotional effects, and triggers further user activities [4, 5].

A systematic monitoring of the configurator landscape reveals that web-based product configurators are modified and rebuild regularly, indicating that the digital behavior of customers and their respective expectations on the offered interaction space changes over time.

This paper highlights changes of existing product configurator offerings with regard to their respective industries and examines patterns of user interface changes.

2 The Product Configurator Landscape

2.1 Status Quo of Web-Based Product Configurators

When it comes to understanding the status quo of online product configurators, the Configurator Database Research Project (www.configurator-database.com) proves to be a helpful resource of monitored data. This project was started in 2007 with the aim to give a continuously updated overview of the world of configurators. As mass customization gains more importance, the number of configurators in the database is increasing. But also a significant number of product configurators vanished over time and were removed from the database. In 2007 the project team could identify 600 web-based product configurators that were accessible online, in 2013 already 900 configurators were identified, in 2014 the number grew to 970 configurators, while in 2015 a new milestone could be proclaimed: more than 1000 online configurators could be identified, and at the end of the year, 1050 configurators were listed in the database. At the end of 2016, this number grew to an impressive 1200 online configurators [1].

The customizable products of the Configurator Database are very diverse, so they have been categorized in 17 industries (Fig. 1.: industries with description and some product examples for each industry).

When taking a closer look at the status quo of 2016, most of the online accessible configurators can be found in the industry *House & Garden* with 177 listed entries, followed by *Apparel* ($n = 167$) and *Accessories* ($n = 144$) [1] (Fig. 2).

When not just looking at the configurator frequency in industries but at particular products, the most popular products for mass customization are cars, t-shirts,

Industry	Description	Product Example
Accessories	Everything that can be worn (except clothing and footwear)	Jewelry, bags, hats, belts, cases, glasses , watches, gloves
Apparel	All kinds of clothing & fabrics (except footwear)	T-Shirts, pants, mixed clothing, underwear, socks, jackets, bikinis
Beauty & Health	Care products and cosmetics	Make up, lipsticks, shampoos, soaps, lotions, perfumes
Electronics	Electronic devices and applications	Computers, notebooks, usb sticks, cables
Food & Packaging	All kinds of food and beverages	Beers, wines, chocolates, cookies, candy, cereals, tea, coffee, snacks, labels
Footwear	Everything that is worn on the feet	Sneakers, flip flops, high heels, boots
Games & Music	Everything for music and gaming time	Musical instruments, board games, puzzles, playing cards
House & Garden	All kinds of products for house and garden	Kitchens, garages, elevators, fences, furniture, doors, windows, saunas, tables, lamps, carpets, door knobs, light switches
Industrial Goods	Different products mainly for manufacturers	Steel, chemistry, medicine, safety systems
Kids & Babies	Products designed specifically for babies and children	Blankets, bottles, diapers, dolls, baby accessories, children's books, playgrounds, soft toys
Motor Vehicles	Cars and other vehicles	Automobiles, motor bikes, yachts, campers
Office & Merchandise	All kinds of office supplies and merchandise	Folders, pens, business cards, stamps, pencils
Paper & Books	Printed products and photo products	Books, cards, calendars, wallpaper, photo canvas, notebook, wrapping paper
Pet Supplies	Products for Pets	Pet food, pet accessories, aquariums
Printing Platforms	Platforms which offer products of various industries	Giftware, photo products, 3D products, engraved products
Sportswear & Equipment	Equipment and clothes for sports	Skateboards, bicycles, snowboards, golf balls, diving suits, jerseys
Uncategorized	Products which do not fit in any other industry	Tissue Boxes, swords, gemstones, signs, locks, coins

Fig. 1 Industries of the Configurator Database [1]

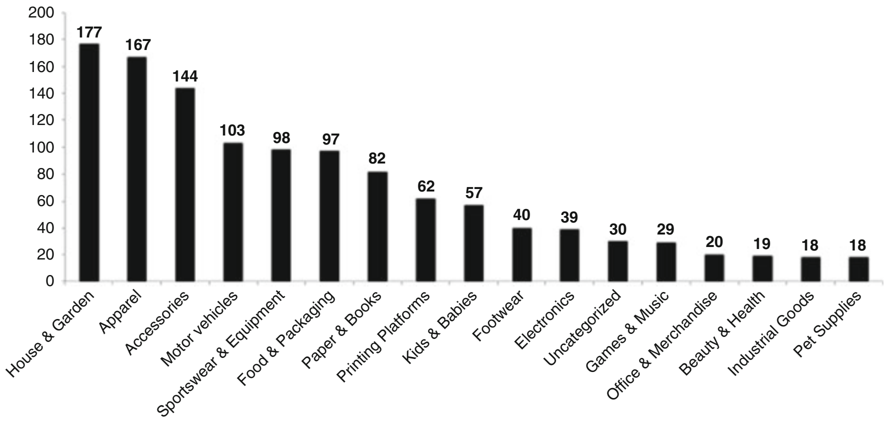

Fig. 2 Industry ranking in the Configurator Database ($n = 1200$) [1]

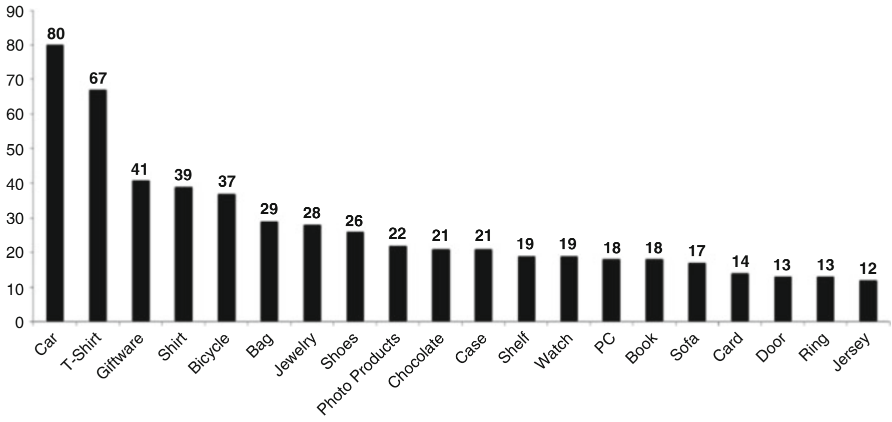

Fig. 3 Top 20 of the most popular products in the Configurator Database ($n = 1200$) [1]

giftware, and shirts. Besides these, there are also a lot of unusual customizable products like chimneys and aquariums which occur only once in the database (Fig. 3).

The field of mass customization shows significant year-on-year changes in the number of configurators, which becomes obvious when analyzing and updating the Configurator Database. When comparing the identified configurators in the Configurator Database Report 2016 with those of the Configurator Database Report 2015, 204 (19%) of the 1050 listed product configurators in 2015 disappeared in the following 12 months. On the other hand, 354 (34%) new product configurators were introduced to the online market, which indicates that mass customization approaches gather momentum.

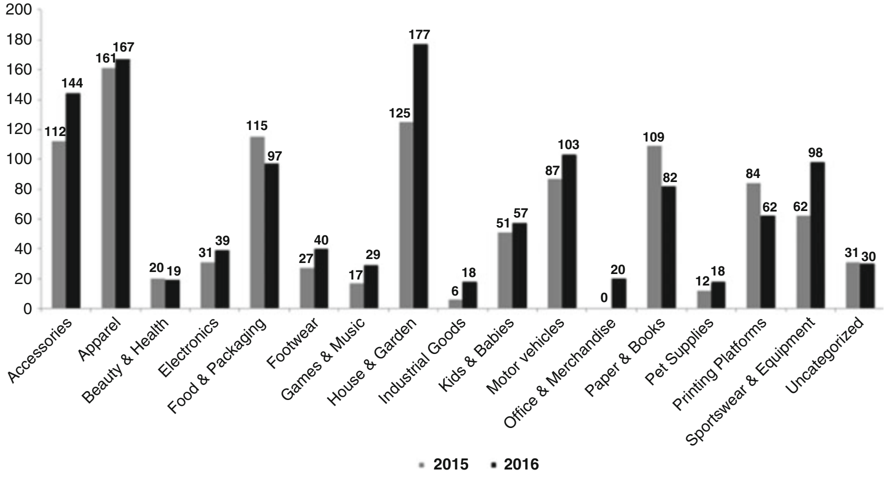

Fig. 4 Numbers of product configurators per industry [1]

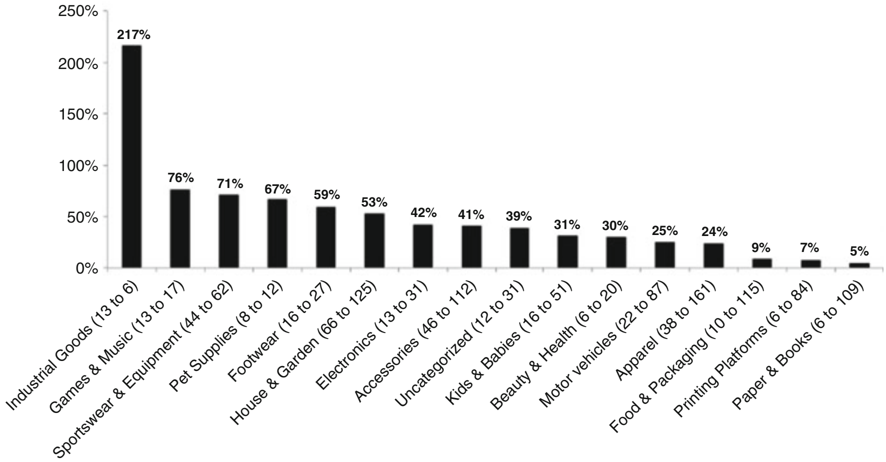

Fig. 5 Added configurators 2016 ($n = 1050$) [1]

The biggest changes can be found in the industries *Industrial Goods*, *House & Garden*, and *Sports Equipment*, as the number of configurators has extremely expanded. On the contrary the configurators in the industries *Food & Packaging* and *Paper & Books* are declining (Figs. 4 and 5).

3 Empirical Analysis

3.1 Research Aims

Existing research shows that there is a constant flow in the landscape of online configurators. Completely new customizable products with the respective new configurators appear online, while others are removed [6]. But what happens with configurators that remain online over years for products that are established on the market?

The aim of this study is to get a better insight into updates of remained online configurators within the last year: Did the user interface of configurators of various industries change within 1 year, or did they stay the same? Which industry shows the strongest trend concerning changes in user interfaces? When taking a closer look at the industry with the strongest change, which user interface components did change? What do the user interface changes mean for further research?

The output shall help to get a first idea if and which industries have a rapid change concerning their user interfaces. Furthermore it shall show which user interface components underlie a change by taking a closer look at the product configurators of one industry. Nevertheless the main aim is to figure out whether or not lean configuration processes should be forced.

3.2 Method and Setting

The method used for this study is a quantitative analysis to detect changes according the user interfaces of configurators in various industries from 2015 to 2016. In order to reveal differences of configurator user interfaces within 1 year, the Configurator Database Reports 2015 [7] and 2016 [1] were compared.

In the first place all industries are analyzed whether their user interface has changed or not within 1 year. This should give a better idea which industry has the biggest movement. For this analysis, only the configurators which remained active were considered, which means that removed or added configurators are not included.

As the aim of the second part of the analysis is to get a better idea of what components within the user interface have changed, it will focus on the industry with the highest level of change. Furthermore only the biggest product category will be considered as comparing different product categories may not provide valid results.

The proceeding to identify changes concerning the user interface is the following:

1. The sample of configurators of one industry which changed their user interface within 1 year is taken from the Configurator Database Reports 2015 [7] and 2016 [1] (Appendix Table 1).
2. The stored user interface of every configurator from 2015 [7] is compared with the one from 2016 [1]. If a configurator already changed until June 2017, the current version of the respective user interface was used.
3. The gathered data is used to define a set of categories to make the user interface changes comparable.
4. The sample is evaluated according to the defined categories.
5. The output shall disclose which user interface components underlie the biggest change.

The following set of categories was defined for the quantitative analysis:

- *Visual appearance*:
  - Did the visual appearance change (colors, font, looks, icons, etc.)?
- *Configuration steps (navigation)*:
  - Did the amount of configuration steps change or remain the same? If it changed, are there more or less steps concerning the year before?
  - Did the wording of the configuration steps change? This concerns only the steps/option which remained the same.
  - Did the position and/or alignment of the configuration steps within the user interface change?
  - Did the position of the process buttons change, if existing before? Process buttons lead the user to the next or previous configuration step.
- *Product visualization*:
  - Did the offered views of the product visualization change?
  - Did the background situation of the product visualization change?
  - Did the position (alignment) of the product visualization change?
  - Did the size of the product visualization become bigger, smaller, or stay the same?
- *Others*:
  - *Product price*: Did the position of the product price change?
  - *Configuration summary*: Did the position (alignment) of the summary (button or full visible) change – only concerning summaries that are not integrated in the process steps?

4 Results and Key Findings

4.1 User Interface Changes of Product Configurators from 2015 to 2016

The Configurator Database Reports of 2015 and 2016 show considerable movements concerning removed and added configurators. When taking a closer look at the configurators that remained the same in 2015 and 2016, Fig. 6. shows that there has been a change of user interfaces of some configurators in each industry.

Identifying the Industry with Most Updates To figure out which industry represents the highest degree of updates concerning the user interface, the graphic below ranks the top 10 industries concerning their percentage share of all remained configurators. The *Motor & Vehicle* industry is leading with 75%, followed by *Paper & Books* with 47% and *Apparel* with 43%. Therefore the focus for the following quantitative analysis will be put on the *Motor & Vehicle* industry (Fig. 7).

When taking a closer look at the *Motor & Vehicle* industry, the leading product category that has changed most within the *Motor & Vehicle* industry is cars with 52 configurators.

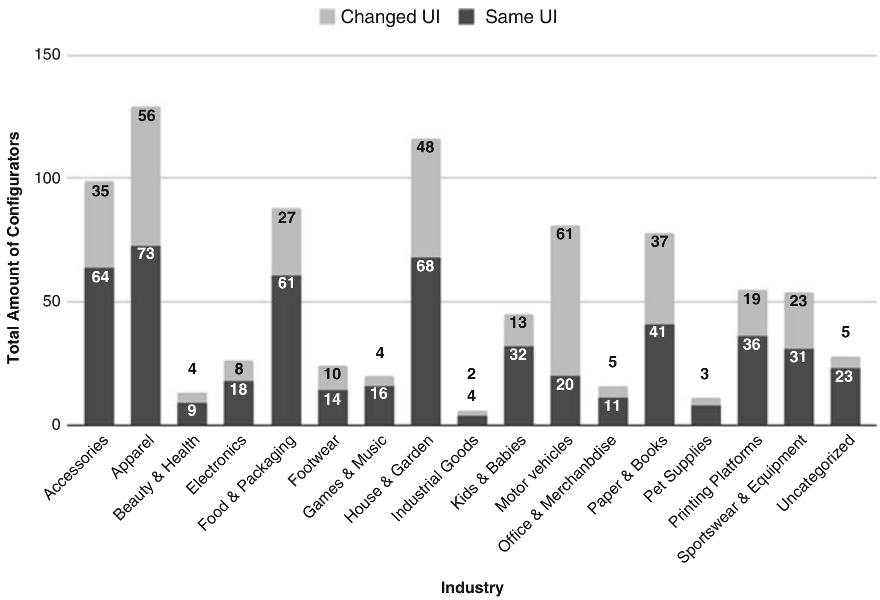

Fig. 6 Changed interfaces per industry from 2015 to 2016 in total

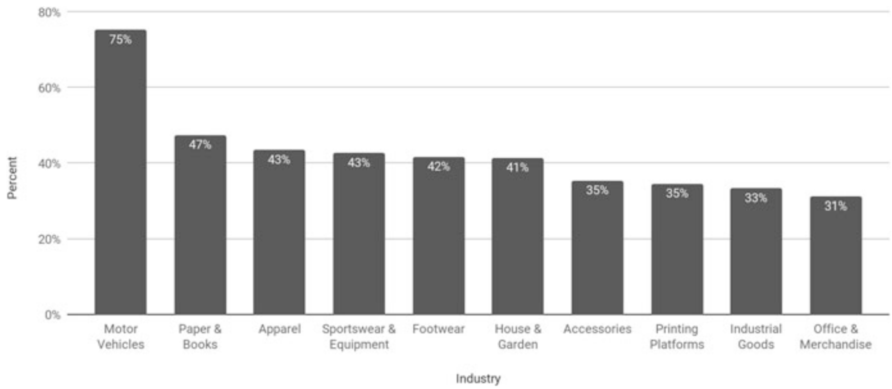

Fig. 7 Top 10 changed user interfaces per industry from 2015 to 2016 in percentage

4.2 User Interface Changes of Car Configurators

As the leading product category within the *Motor & Vehicle* industry is cars, this quantitative study was conducted with 52 car configurators that experienced a change from 2015 to 2016.

In the following, the results are summarized according to the defined categories described in Sec. 3.2. Setting and Methods.

Changes of Visual Appearance The visual appearances of a configurator are the colors, fonts, icons, button design, etc. that are used. The study shows that all of the 52 analyzed car configurators changed their visual appearance from 2015 to 2016. Three configurators changed only the visual appearance and no other components. For example, the Bentley configurator solely changed the visual appearance from 2015 to 2016, while the features and the navigation structure remained the same (www.bentleymotors.com).

Changes of Configuration Steps (Navigation) The configuration steps guide the user through the possible configuration options.

- *Amount*: As seen in the Fig. 8., 75% of the 52 analyzed car configurators have changed the amount of the offered configuration steps. 50% have more steps than in 2015 and 25% less than in 2015. Only 17.3% stayed with the number of steps from 2015 to 2016. For 7.7% it was not possible to make a valid statement, as the screenshot of 2015 didn't concern the needed information.
- *Wording*: The wording of the steps is also an essential part within a customization process. Users get a better idea what they are expecting in each step, and companies have the possibility to use their own corporate language. The research shows that 40 out of 52 car configurators changed the wording of the configuration steps, preconditioned that the step itself stayed the same from 2015 to 2016 (Fig. 9).

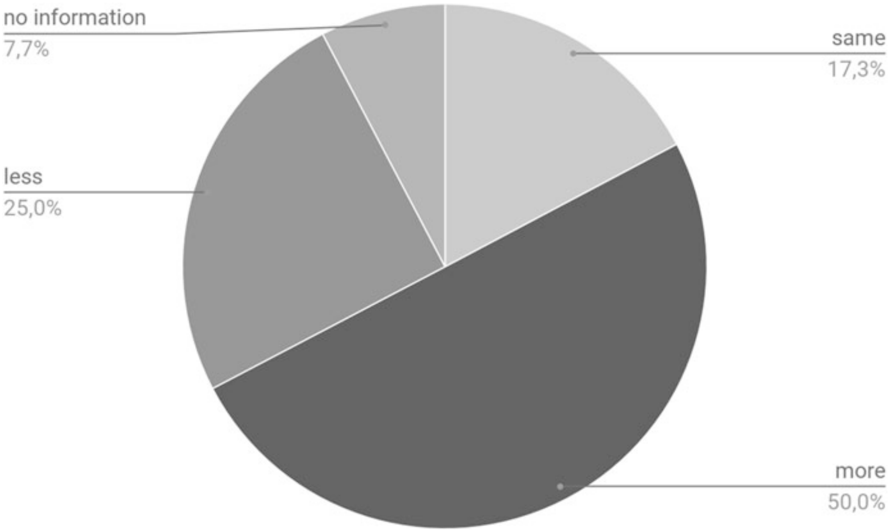

Fig. 8 Changes in amount of configuration steps ($n = 52$)

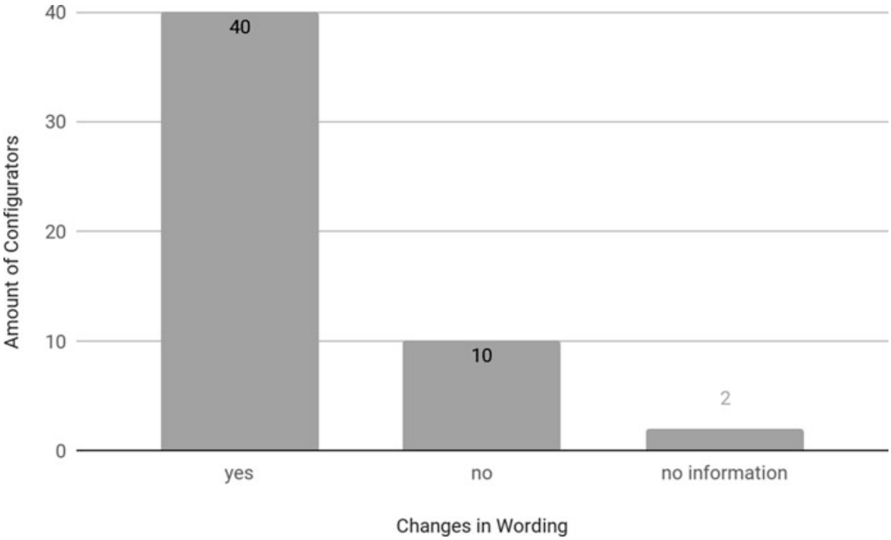

Fig. 9 Changes in wording of configuration steps ($n = 52$)

- *Position and alignment*: 57.7% of the analyzed car configurators changed the position and/or alignment of the configuration steps. For example, the car configurator of Ford Germany aligned the configuration steps in 2015 horizontally below the product visualization and in 2016 vertically on the left side of the product visualization (www.ford.de).

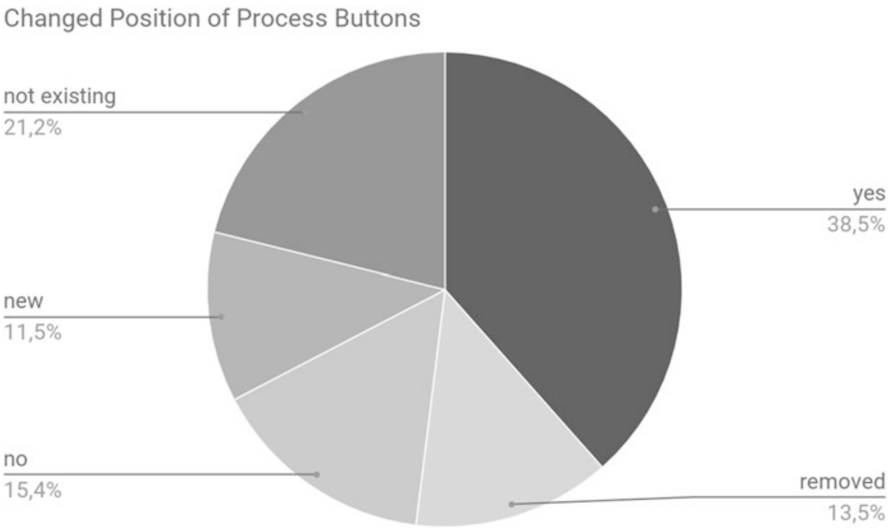

Fig. 10 Changed position of process buttons ($n = 52$)

- *Process button*: The process button guides users from one configuration step to the next or previous. The button shall give users a guidance; therefore, the positioning is relevant. 38.5% of the 52 analyzed car configurators changed the position from 2015 to 2016. However 13.5% removed the process button within this timeframe and 11.5% added one (Fig. 10).

Changes of Product Visualization The visualization of the customizable product is essential in a configuration process. It helps users to get a better idea of the product they may purchase and decreases doubts [7]. In the following, changes concerning different aspects of the product visualization are described.

- *Views*: As cars are more complex products, car configurators often offer the product visualization in several views to get a better idea of the product. 35 of 52 car configurators (67%) changed the amount of views from 2015 to 2016. For example, Alfa Romeo offered in 2015 only two external views, whereas in 2016 a 360-degree view (www.alfaromeo.de).
- *Visualization background*: Visualization background refers to the environment in which a car is presented. This can be, for example, a city, special landscape, in front of a house, or just in a unicolor space. 46.2% of the 52 car configurators changed their background visualization from 2015 to 2016.
- *Position:* The position of the visualization may be seen as a crucial factor as a company has to decide in which sector of the screen it makes the configuration process easy and pleasant for a user. 53.8% of the 52 car configurators changed the position of the product visualization from 2015 to 2016. For example, the car

configurator of GMC placed the visualization of the customizable car on the right side of the process steps in 2015 but switched the visualization and process steps in 2016 (www.gmc.com).

- *Visualization size:* The size of the product visualization may be an interesting field of research as a company has to decide to assess the importance between a visual, emotional component (the product visualization) and the more technical component (the configuration options). 29 of the 52 car configurators (55.8%) didn't change the size of the product image. Sixteen (30.8%) car configurators made the product visualization bigger, and seven (13.5%) made the product visualization smaller. The car configurator of Lexus Germany decided to enlarge the product visualization from 2015 to 2016. The configuration steps get less priority, as they are positioned at the very bottom and they are collapsible (www.lexus.de).

Other Changes Two more aspects have been evaluated, which were analyzed detached from the previous categories. In the following the positioning of the product price and the configuration summary are described in detail.

- *Product price:* The display of the product price is substantial in a configuration process as it gives the user cost transparency over the chosen options [8]. So the positioning of the product price on the screen can be seen as an important issue. 37 (71.2%) out of 52 car configurators changed the position of the product price from 2015 to 2016. Two configurators added the price to the configurator and one didn't show the price at all. Ford Germany, for example, changed the positioning of the price from the lower right side in 2015 to the upper right side.
- *Configuration summary:* The configuration summary presents all custom options that were chosen within the configuration process and give the user an overview of the individualized product before further purchasing decisions [7, 9]. 61.5% (32) of the 52 car configurators cover the summary in the process navigation, so the position changed when the whole process navigation changed. Fourteen of the remaining configurators display the summary as a button. 13 of the 14 summaries changed their position and one didn't. Five configurators didn't offer a summary as button or in the process navigation at all. One configurator added a summary in 2016.

4.3 Premise of the Analysis

This quantitative analysis gives an overview of changed user interfaces of various industries within 1 year, with a special focus on the *Motor & Vehicle* industry. Although the study takes a closer look at the changes of user interfaces of car configurators, the results do not give information about whether these changes have an impact on purchasing decisions of users or why companies decided to change the user interface.

5 Summary and Outlook

In times where user needs are getting more and more into focus and product offerings change in consequence of developing user needs, the aim of this study is to take a look at the status quo of product configurators of various industries. The basis of this study are the Configurator Database Report 2015 [7] and Configurator Database Report 2016 [1], which both offer a collection of more than 1000 online product configurators in 17 industries.

In the first part of this paper, the status quo and changes of the product configurator landscape are elaborated. The second part of this paper focuses on the quantitative analysis, which delivered the following results. The product configurators that remained online from 2015 to 2016 were analyzed concerning interface changes. The analysis shows that 75% of the user interfaces of the *Motor & Vehicle* industry have changed within 1 year, followed by the industries *Paper & Books* with 47% and *Apparel* with 43%. Focusing on the changed user interfaces of the *Motor & Vehicle* industry, the leading product category is cars with 52 configurators. These 52 car configurators have been analyzed according to predefined categories, namely, changes in visual appearance, configuration steps (amount, wording, position, process buttons), product visualization (views, visualization background, position visualization size), and the positioning of the product price and the configuration summary.

The visual appearance (e.g., colors, fonts, style, etc.) of all analyzed 52 car configurators has changed from 2015 to 2016. 75% of the 52 analyzed car configurators have changed the amount of the offered configuration steps, whereas 50% offer more steps and 25% less steps compared to 2015. The wording of the configuration steps was changed by 40 of the 52 car configurators. 57.7% of the 52 car configurators changed the position and/or alignment of the configuration steps. 67% changed the amount of views offered for the product visualization; furthermore, 46.2% of the 52 car configurators modified the background visualization and 53.8% changed the position of the product visualization. 29 of the 52 car configurators (55.8%) didn't change the size of the product visualization; however, 16 (30.8%) made the product visualization bigger and 7 (13.5%) made the product visualization smaller. 71.2% of the 52 analyzed configurators changed the position of the product price. 61.5% cover the customization summary in the process navigation; the 14 remaining configurators display the summary as a button. 13 of the 14 summaries changed their position and one didn't.

The study gives an overview of changed user interface elements of car configurators. It proves that there is a flow concerning the position, alignment, and other characteristics of user interface elements.

However, the analysis doesn't reveal why 75% of companies in the *Motor & Vehicle* industry have such a high tendency to change their user interfaces within 1 year. Some of the screenshots of the Configurator Database Report 2016 [1] are not even up to date anymore, so it can be assumed that car configurator may change much more rapidly than configurators of other industries. For further research, it would be interesting to interview car companies to find out why they have such a high tendency to change the user interface of their configurator and what their main impulse is to change them (user testing, customer feedback, market research, consulting company, etc.). Another important field of research is if companies offering car configurators work with systems that allow them to change the user interfaces rapidly and allow them to react on trends and desires or if they rely on more complex and time-consuming systems.

Appendix

Table 1 Sample of 52 car configurators [1, 6]

No.	Company name	URL
1	Alfa Romeo	http://www.alfaromeo.de
2	Audi DE	http://www.audi.de/de/brand
3	Bentley	http://www.bentleymotors.com
4	BMW USA	http://www.bmwusa.com
5	Buick	http://www.buick.com
6	Cadillac	http://www.cadillac.com
7	Chevrolet DE	http://www.chevrolet.de
8	Chevrolet USA	http://www.chevrolet.com
9	Chrysler	http://www.chrysler.com
10	Citroen	http://www.car-configurator.citroen.co.uk
11	Dacia DE	http://www.dacia.de
12	Dodge	http://www.dodge.com
13	Ferrari	http://www.ferrari.com
14	Fiat DE	http://www.fiat.de
15	Fiat USA	http://www.fiatusa.com
16	Ford DE	http://www.ford.de
17	Ford USA	http://www.ford.com
18	GMC	http://www.gmc.com
19	Holden	http://www.holden.com.au
20	Honda DE	http://www.honda.de
21	Honda USA	http://www.honda.com
22	Hyundai USA	http://www.hyundaiusa.com
23	Jaguar	http://www.jaguar.com
24	Jeep	http://www.jeep.com
25	Kia US	http://www.kia.com
26	Land Rover	http://www.landrover.com
27	Lexus DE	http://www.lexus.de
28	Lexus USA	http://www.lexus.com

(continued)

Table 1 (continued)

No.	Company name	URL
29	Lincoln	http://www.lincoln.com
30	Maserati	http://www.maserati.com
31	Mazda UK	http://www.mazda.co.uk
32	Mazda USA	http://www.mazdausa.com/
33	Mini AT	http://www.mini.at
34	Mini USA	http://www.miniusa.com
35	Mitsubishi	http://www.mitsubishi-motors.at
36	Nissan DE	http://www.nissan.de
37	Peugeot	http://www.peugeot.at
38	Porsche AT	http://www.porsche.at
39	Ram	http://www.ramtrucks.com
40	Renault	http://www.renault.de
41	Seat	http://www.seat.de
42	Skoda	http://www.skoda.at
43	Smart	http://www.smartusa.com/
44	Subaru US	http://www.subaru.com
45	Suzuki DE	http://auto.suzuki.de
46	Tesla Motors	http://www.teslamotors.com
47	Toyota DE	http://www.toyota.de
48	Toyota USA	http://www.toyota.com
49	Volkswagen AT	http://www.volkswagen.at
50	Volkswagen DE	http://www.volkswagen.de
51	Volkswagen USA	http://www.vw.com/
52	Volvo	http://www.volvocars.com

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Part V
Solution Space Development and Variety Management

Data-Driven Product Family Modeling with Feedback

Thomas Ditlev Brunoe and Kjeld Nielsen

Abstract In order to become a successful mass customizer, companies must be in control of their product variety. This is to ensure that the product variety is sufficient in order to satisfy the range of customer demands but also to ensure that there is no excess variety, which compromises efficiency in business processes and manufacturing processes. This is often addressed by establishing product family models which represent the variety in a specific product family and any constraints there may be. In this paper, we first present a literature review of the currently existing product family modeling methods, in which it is concluded that most current methods are stand-alone, document-based methods, which largely do not consider integration with other product data systems or feedback from production and products. We then propose a number of new approaches to product family modeling, which utilizes data from other systems such as ERP and PDM, which enables a more fact-based modeling process. Furthermore, the proposed approach enables feedback loops into the product family model, which is possible due to advances in connectivity (IOT applications). The new approach will enable better qualification of decisions regarding product variety management once implemented.

Keywords Mass customization · Product modeling · Product family modeling · Solution space development · Product variety

1 Introduction

The business strategy mass customization was introduced in the late 1980s and gained more and more attention throughout the 1990s [1, 2]. Today, mass customization is an integrated part of many companies' business, but it is still being debated how companies should approach the implementation of mass customization. Mass

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customization was initially adopted by the manufacturers of durable consumer goods such as cars and computer, but today, the application of mass customization is more widespread. Originally, mass customization was thought a strategy for mass producers, i.e., high volume and low variety, to increase variety and thereby differentiate themselves from the competitors thus gaining market share and ability to increase markups. Today, however, more and more companies in other types of industries are considering adopting mass customization as their strategy. Many engineer-to-order companies have acknowledged that some of the methods and tools used by the early mass customizers can be used to address the issues experienced by them in relation to selling and producing high-variety products [3]. Additionally, the service industry and consumables, e.g., the food industry, are beginning to adopt mass customization. In most cases, when adopting mass customization to an industry which is not physical durable goods for the consumer market, the tools and methods need to be adapted more or less to accommodate the differences in requirements.

In their publication “Cracking the Code of Mass Customization” [4], Salvador et al. presented that companies pursuing mass customization need to have three fundamental capabilities, apart from the capabilities needed to run any company, mass customizer or not. These three capabilities are (1) solution space development, (2) choice navigation, and (3) robust process design. The capability “solution space development” refers to a company’s ability to identify the differences in customers’ preferences and develop products which address these preferences. “Choice navigation” is helping the customers in selecting or defining the product they desire in an easy manner, so that it does not become a burden to the customer. This can be done in a number of different ways, but quite often, choice navigation is implemented by using a product configurator. “Robust process design” is having business processes and manufacturing processes which are capable of handling, selling, and producing products of high variety.

One discipline which is essential to master for many mass customizers is product family modeling. A product family is a range of products which share certain characteristics, sometimes based on a product platform. A product family model is thus a model which is intended to represent the product variety which can be configured, bought, and produced for a customer. A product family model must thus contain different information, typically including the elements below:

- Information on which elements can be included in the product. If the product is modular, these elements will typically be modules.
- Information on how these elements can be combined, i.e., rules or constraints.
- Information on how combinations of different elements, e.g., modules, result in different product characteristics such as appearance or performance.
- Information on pricing – how to translate customer selections into a price of the product.
- Information on how to translate the configuration into an actual product. For physical products, this may be a bill of material along with other additional information.

These elements constituting the product family model are typically implemented in a configurator and thus serve as the specification for programming or modeling in a product configurator development tool. Hence, the product family model becomes an important enabler for realizing an effective choice navigation capability, one of the three fundamental mass customization capabilities. Another fundamental mass customization capability is solution space development, where the companies determine which product variety should be offered to customers and how this is implemented in the actual products, often through developing product families. One output of this process is thus much of the information that should be included in a product family model, and hence product family modeling becomes a medium that connects the activities in solution space development with the activities in choice navigation.

As long as mass customization has been researched, product family modeling has also been a topic of interest for scholars. Several methods for modeling product families have been proposed, and some have been successfully applied in industry. However, most of these methods are somewhat isolated tools, which to some degree seem like single document-based models, which are not integrated with any other systems such as product PLM, ERP, or configuration systems. We hypothesize that there is a potential in extending the product family modeling activity to also integrate other IT systems and enabling feedback of information. The research question, which we address in this research, is thus:

> What are the major streams of literature in product family modelling supporting product configuration, and how may product family modelling be extended to support feedback from other systems?

2 Methods

To address the research question, we apply a classic literature retrieval approach. We first define an initial search string, which is applied in Thomson Reuters Web of Science. The search string applied is the following:

```
("product family model" OR "product family modelling" OR "product
family modeling" OR "product model" OR "product modelling" OR
"product modeling") AND ("mass customization" OR "product
configuration" OR "product configurator" OR "configurator")
```

This first part (before the AND) of the search string accommodates for differences in the actual term used to refer to product family modeling. Some authors apply the term product modeling instead of product family modeling. The second part of the search string ensures that only modeling methods related to product configuration or mass customization are included, since product modeling is used in many other application areas. The initial search retrieved 77 different publications. Once results were retrieved, we performed an initial screening for relevance on title and abstract before reading the full papers. We choose only to review the methods presented within the last 10 years, which narrows the number of publications to 48.

Fourteen publications were excluded after reviewing the abstract as they did not address product family modeling, leaving 34 publications for further analysis.

3 Review of Current Product Family Modeling Methods

Analyzing the literature published in relation to product family modeling, it appears that there are a number of different themes that the contributions seem to address. One group of contributions is centered around the method product variant master, sometimes referred to as product family master plan [5–8]. These contributions revolve around letting product experts model product families in a product tree, followed by describing each model element using CRC (class responsibility collaborator) cards, sometimes followed by class modeling using UML class diagrams. This method has proven very useful in many companies applying this method for configurator development as well as standardization projects. The advantage of this method is that it is very easily understood and is thus easy to teach and to use. On the other hand, the method is primarily document based, which makes it difficult to on one hand use the information directly when developing a configurator, and on the other hand, it makes it difficult to utilize existing information from other systems to semiautomatically perform modeling tasks.

A few contributions focus on developing product family modeling methods for specific contexts, such as ETO products [9–12], the fashion industry [13], or integrated control systems [14]. Another group of contributions focus on modeling geometry. Gembarski et al. [15] propose modeling geometry using shape degree of freedoms, while other authors study how product family modeling can be implemented in CAD/CAE systems [16–18].

Several contributions address how to include information supporting the production system in the product family model, thereby enabling that the production processes can be automatically or semiautomatically configured using the information created in the product configuration process.

Liu et al. address this issue from a data exchange perspective and propose how [19], based on a product model, product data can be exchanged between configuration and production system using XML and STEP technologies. Dean et al. [20] present a framework and implementation of generating production information, including bills of materials and work instructions. The framework has been successfully implemented in various companies enabling data transfer from the product configurator to production. Similarly Matias et al. [21] describe a method for automatically generating bills of materials based on product configurator output.

Aldanondo and Vareilles [22] describe, in a very extensive concept, how requirement constraint modeling can be applied to model the constraints between the upstream requirement configuration and the subsequent process configuration.

Various other contributions addressing on product family modeling have also been published addressing isolated topics such as optimization [23, 24], using colors to aid the modeling task [25], or using ontologies to create models of product families [24, 26–28].

As presented above, several valuable contributions exist, which address product family modeling. A few of these contributions also address how to integrate the product configurator with the manufacturing activities. From several case studies we have done in the past, we have experienced many companies actually doing integration from the product configuration system to the production system; however, all of these examples are invented from scratch for each application, and no frameworks, focused methods, or dedicated modeling procedures have been followed. This indicates that there is in fact a great potential in implementing this integration and there thus is a potential in researching this further. From the literature study above, we can also conclude that no contributions which we could identify address the flow of information from the production system and beyond back to the product family models for development and feedback purposes. For this reason, we do an analysis of the potentials in this mechanism in the following chapter.

4 Potentials in Data-Driven Family Modeling

Figure 1 illustrates a typical process chain related to product family modeling. The first process is the actual product family modeling, which is part of the solution space development activity. The output of product family modeling is used for developing a product configurator, which is consequently used in the product configuration process, when customers or salespeople define a product which may afterward be sold. Given the product is sold, part production (the production of components or parts needed to assemble the product) may be initiated, given it is a made-to-order setup, where components or modules are custom made. This process may however be decoupled from the process chain given the company follows an assemble-to-order strategy. The parts are fed to the assembly process, where the

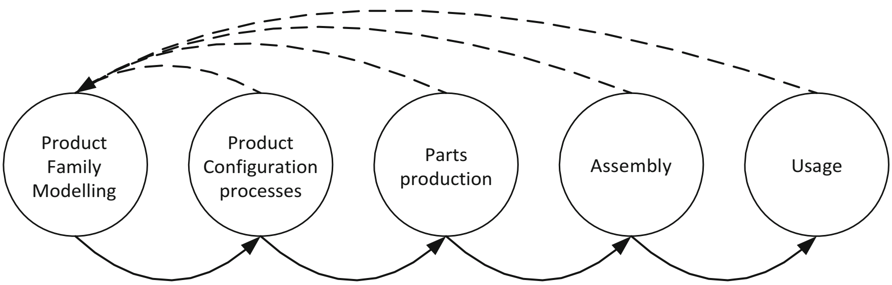

Fig. 1 A generic product configuration process chain

final product is assembled conforming to the configuration performed in the product configuration process. Subsequently, once the product has been assembled, it is distributed and enters the usage phase with the customer. These are the process chain that is likely to be found in some variation in almost any physical goods manufacturer. The flow is illustrated in Fig. 1 by the solid arrows.

However, since data is generated throughout this process chain, and industry sees a general tendency to store more and more data from various processes, we wish to analyze how this data can be used if fed back to the product family modeling process. These potential feedback loops of information are shown in Fig. 1 as dashed arrows and will be addressed one by one in the sections below.

4.1 Product Configuration Process

The information generated in the product configuration process itself may hold information which is relevant when performing product family modeling. This claim is supported by the findings of Nielsen et al. [29, 30], who proposed a set of metrics which could be used to evaluate the performance of the choice navigation and solution space development in a mass customization company. Although some of these metrics are more aggregated, other metrics give indications of, e.g., utilization and frequency of certain configuration variables and modules which are included in the product family model. This gives input to the ongoing process of adjusting the solution space in the company, since variables and modules which are rarely used contribute to excess cost and complexity. Modules which are rarely chosen in configuration add to the complexity cost in product management as well as in production processes since modules which are rarely sold will imply lack of economies of scale for those modules. Also, variables which are rarely used in the configurator may imply excess costs for maintaining the configuration system, when updating the system, testing after doing updates, etc. Finally, unnecessary variables in the configurator may confuse the customers using the configurator, increasing the "burden of choice" which may lead to lost sales.

Particularly for engineer-to-order companies, there is a common challenge that the product configurator can rarely contain all variety required by customers. This implies that companies must somehow handle requests for non-configurable variety in their IT systems. Often, this is handled by manually entering or adding generic modules or elements to the configuration in the product configurator, which is handled by an engineering department later on in the process. This variety however may be beneficial to add to the product family model if it is expected to be sold again in the future. The information generated in this process regarding the non-configurable variety may be relevant to feed back to the product family modeling process.

4.2 Part Production

Also when producing parts for a customized product, some information may be valuable in the product family modeling process.

In some cases, a product family model is established based on an existing product portfolio which is already being manufactured. In this case, the information in the company's ERP system telling which parts and modules have been manufactured can serve as a gross list of elements to include in the product family model. Hence, the parts can serve as the foundation or building blocks for establishing the product family model instead of product experts having to remember or look up all module variants. When a company goes through the process of modeling their existing product families to eventually implement a product configurator, most companies identify excess variety and thus go through a standardization process to address this. The information found from part production will hold information on production volumes per part and can thus indicate if certain parts are very rarely produced and should be phased out c.f. the argumentation in the section above.

One particularly important and often time-consuming part of the product family modeling process is pricing. Pricing is usually to some extent based on costing, and the company's ERP system will often hold information on the cost of producing parts or modules, both expected cost and actual historical cost. By using this information in the product family modeling process, costing can be performed automatically. Furthermore, part or modules which experience large variations in cost, due to, e.g., frequent quality issues, can be identified and possibly excluded from the product family model and replaced by more reliable alternatives.

4.3 Assembly

Many mass customizers utilize the assemble-to-order production mode, where products are assembled according to a customer's configuration once an order is placed. The information generated in this process may also be useful in relation to the product family modeling process. One piece of information is parts or modules are combined and how often combinations occur. Combinations that often occur may imply that certain combination of parts should be integrated into new modules in the product family model, to reduce time and cost of assembly and improve economies of scale. Furthermore, combinations which often occur may indicate that many customers have preferences for this particular combination, and this information could be used to improve the product configurator by, e.g., showing this combination as a predefined default choice.

Another type of information generated in the assembly process may be the labor time used to perform the actual assembly. If certain combinations require excessive assembly times or show high rework rates, this indicates that this particular combination may be inappropriate to offer customers and as such should be excluded from the product family model or the product family model constraints should be revised to address that issue somehow else.

4.4 Usage

The information generated in the usage phase is somewhat more difficult to address, since companies have inherently little control which information flows from their products after they are sold. One piece of information that companies will have is whether customers complain about their products once they start using them. If customer complaints or returns can be linked to what has originally been configured by the customer, analyses could be performed, identifying correlations between customer satisfaction and which choices they have made in the configurations.

Additionally, looking at the current trends of IOT connectivity, Industry 4.0, etc., it is likely that companies in the future will be able to gather much more information on how the products are used. Although the ethics are continuously debated, many companies already today receive a steady stream of information on their products in use, e.g., phones, computers, cars, etc. This information may also be very useful for the companies when doing product family modeling, as they will be able to tell which features that are chosen in the configuration are actually being used. Moreover, knowing which features customers use in the products could potentially help develop the product family model and enhance the ability of the customers in matching the product with their needs.

5 Conclusions and Future Work

Based on the sections above, we conclude that there is a potential in establishing a formal and data-driven feedback loop to the product family modeling process. However, we have not been able to identify any literature documenting this, and we have not seen any companies doing it in practice except informal document- and experience-based procedures. Most of the information needed for the feedbacks proposed above will be readily found in most mass customizers' ERP systems; however, the implications of implementing the feedback and the potential benefits are yet unknown. However, since there is a general trend toward making data-driven decisions in industry today, this could be one step toward achieving fact-based, data-driven decisions when doing product family modeling.

The above proposed feedback mechanisms can be regarded as use cases for a new modeling method. Future steps toward developing methods and tools supporting this would be developing an information model describing the structure of the different data holding the relevant information. This may be a challenging task, since product family models, configurators, ERP systems, and MES systems traditionally have very different structures. Once the information model is established, we will conduct experiments with case data one loop at a time, first including data from the configurator, then from the parts production, etc. Once this is done, we can start implementing prototype systems in companies to evaluate the validity of this proposed solution.

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Production Platform Development Through the Four Loops of Concern

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Abstract Managing product variety is still an issue in the industry and one that gets a lot of attention. Among several ways to address this issue is the development of platforms. Platforms, for instance, coupled with the use of reconfigurable manufacturing systems, can potentially enable manufacturers to deal with a more dynamic market, an increase in variation and decrease in product lifecycle. The development of these platforms and systems is often difficult to begin and even more so to finish. This paper presents a method for developing and codeveloping product and production system platforms, using concepts from the field of software architecture development. Development and implementation of the method were carried out through case studies in two Danish companies. The method is an iterative approach consisting of four loops with four steps each. It facilitates the utilisation of concepts and tools from software architecture development during the platform development process.

Keywords Production platforming · Platform development · Codevelopment

1 Introduction

With the advent of the Fourth Industrial Revolution, manufacturers face countless opportunities and challenges—new as well as old. As customer demands become increasingly diverse and new technologies emerge, the need for new variants and faster introduction of new products rises. Managing these changes and variants, and thus their effects on the manufacturer, is crucial to the manufacturer's ability to remain competitive [1]. Implementation of faster development and manufacturing of greater numbers of variants in a cost-effective manner—i.e. mass customisation—have proven a difficult task for many companies [2].

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Platforms have proven useful in creating and managing a variety of products, ensuring the consistency and reusability of assets [3]. These assets can, for instance, be product elements from various phases of the product's life cycle [4] such as product parts, product technology, product functions and production equipment. Depending on the kind of asset targeted by a platform, the platform is given a specific name related to that asset, e.g. product platform [3], process platform [5], technology platform [6], production (or manufacturing) platform [7], etc. These platforms may or may not exist concurrently alongside or within each other.

While always centred on commonality and reusability, several distinct definitions of platforms exist [8]. No suitable definition of production platform has been identified for this study. Instead, we will align the notion of platforms with that of Meyer and Lehnerd [9], defining a product platform as "a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced". As any technical product can be considered a system, it stands to reason that platform strategies, concepts and definitions can prove useful in managing variety in both products and production systems. Indeed, concepts involving joint or codevelopment of (and mapping between) products and manufacturing systems have been gaining footing in research and the industry [7, 10]. Codevelopment allows for concurrent development products and their related production systems through multiple platforms aligned with each other.

Through an increase in standardisation of assets, development of platforms and subsequent platform-based development offers a great number of benefits, as a result of improved commonality and reusability. These include, but are not limited to, reduced system complexity, accelerated time-to-market, reduced development and production costs, easier test and certification and improved plant efficiency [1, 3]. Benefits like these do come at a cost, however, as development of platforms is not a trivial task and may incur large expenses, or commonality may appear as a lack of innovation [3].

Since research on production platforms and platform-based production development is still a relatively small field in comparison to the product equivalent, it can be beneficial to seek inspiration and similarities outside the field itself. Attempts to employ concepts and constructs from the field of software architecture and platforms have previously been made [11–13]. Present effort is an attempt at continuing this line of thought, in order to further research on the development of platforms and codevelopment of products and production. In particular, this study adopts and adapts the conceptual model for architecture descriptions (see Sect. 2.1) presented in ISO/IEC/IEEE 42010:2011(E) (henceforth ISO 42010) [14].

Taking offset in the research identified above, there is a need for research into development of platforms and a potential for concepts from software systems architecture to help fill this gap. To frame this paper, the following research questions have been formulated:

- How can production platforms be developed and documented with the aid of concepts and constructs from the field of software systems architecture?

- Which challenges arise during production platform development, and how can these be addressed?

Based on the concepts presented in ISO 42010, a method for codevelopment of platforms for product and production has been developed, named the Four Loops of Concern (FLC). The purpose of the FLC method is to formalise existing commonality in product and production design. Development and implementation took place during case studies at two Danish companies—a large enterprise with high volume and high variety and a small-medium enterprise with low volume and high variety. The presentation of the method in this paper is focused on the production side, i.e. design of production systems, cells and stations.

This paper firstly presents the conceptual and theoretical background for the FLC method. The method itself is then introduced, followed by a summary of the case studies and the results of these. Finally, the paper is rounded off by a discussion on the method and next steps in development and refinement.

2 Background

With the potential coexistence of multiple platforms each targeting specific types of assets within a company, there is a risk of suboptimisation, as each platform has its own objective for standardisation. Thus, there is a need for alignment between platforms and employing a more holistic approach. Integrated platform development approaches [7, 15] are examples of attempts to realise holistic platform strategies and something currently trending in platform research with the objective of creating practical approaches to achieving consistent and reusable product and production designs [4].

In order to make practical use of platforms, they must be described in a way that is readable and manageable for a variety of stakeholders with particular interests in the platforms. Standardised modelling languages and documentation formats facilitate this by communicating the existence and contents of platforms to relevant stakeholders and allowing developers to actively manage and improve upon the platforms.

2.1 Architecture Descriptions

Although not commonly used in research on product and production architectures, the international standard, ISO 42010, provides definitions and concepts that are useful in developing and describing architectures for systems. Some of the main contributions of the standard are its specification of architecture descriptions and their organisation and expression. To provide context for the rest of the paper, this section focuses on presenting the concept of architecture descriptions, viewpoints and views.

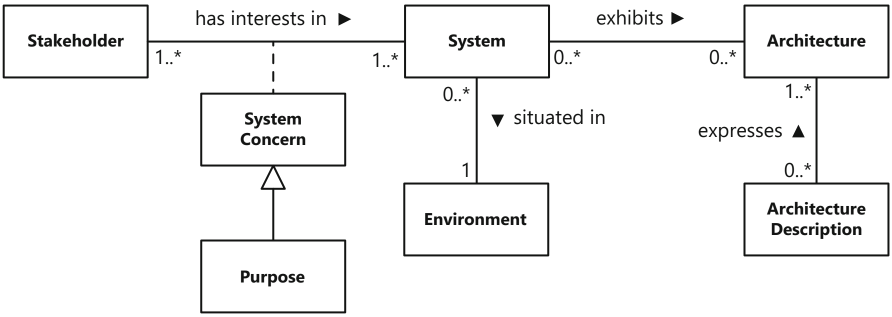

Fig. 1 Context of an architecture description, adapted from ISO 42010 [14]

An architecture description is an expression of the architecture exhibited by a system, as illustrated in Fig. 1. It is a work product of the architecting process—i.e. defining, documenting and implementing an architecture, etc.—whereas an architecture is abstract. Core to the architecture description is the concept of architecture views and viewpoints. ISO 42010 describes the difference between a viewpoint and a view as follows: “A viewpoint is a way of looking at systems; a view is the result of applying a viewpoint to a particular system-of-interest” [14]. A viewpoint—or part of one—may take the form of a template to fill for a requirements specification; the view is the specification itself. While a view addresses concerns held by stakeholders of the system, a viewpoint governs a view and frames concerns for the view to address. As such, the view expresses the actual architecture, directed at stakeholders having a particular interest in the system. It does so through a number of models, dictated by its governing viewpoint.

ISO 42010 itself does not dictate the specific content of the architecture description nor the requirements for the systems and their architectures. This implies that the conceptual model presented in the standard is applicable to any system exhibiting an architecture and thus not reserved for software systems.

The adoption and application of the concepts presented by ISO 42010 gives the opportunity to address a wide audience by using a similar structure and vocabulary. Using the terms and concepts from systems and software engineering furthermore facilitates the usage of methods, models and research in general from outside the field of product and production architectures. Rozanski and Woods [16], for instance, present a catalogue of viewpoints and related concerns for creating architecture descriptions. This catalogue has proven a valuable source of inspiration for this study.

2.2 Platform Descriptions

Bossen et al. [13] introduced the concept of a platform description as an expression of a platform, similar to how an architecture description expresses an architecture.

This is done because platforms are considered a type or subset of architectures, focused on standardising assets. Like the architecture description, the platform description also consists of a number of views, governed by viewpoints, and is a part of the architecture description. The platform itself consists of number of reusable system elements, all of which are identified by the platform description. In the case of production systems, for which the conceptual model by Bossen et al. [13] was developed, system elements are considered on six different levels: (6) network, (5) factory, (4) segment, (3) system, (2) cell and (1) station [17]. A system element on a given level consists of one or more system elements on a lower level, i.e. a network consists of one or more factories and a factory consists of one or more segments, etc.

One of the case companies has already adopted the notion of views in their product development process, although the vocabulary is different. The five viewpoints, shown on the left in Fig. 2, illustrate the five ways a product is viewed during the internal development process, with the dashed line indicating when a product becomes an instance of a platform, i.e. the output of the platform-based development process.

In order to represent a production system in the same manner, and considering the previous statement that products and production systems are both technical systems, the model was reengineered during this study. In the reengineered model shown on the right in Fig. 2, a production side is introduced, along with the concept of

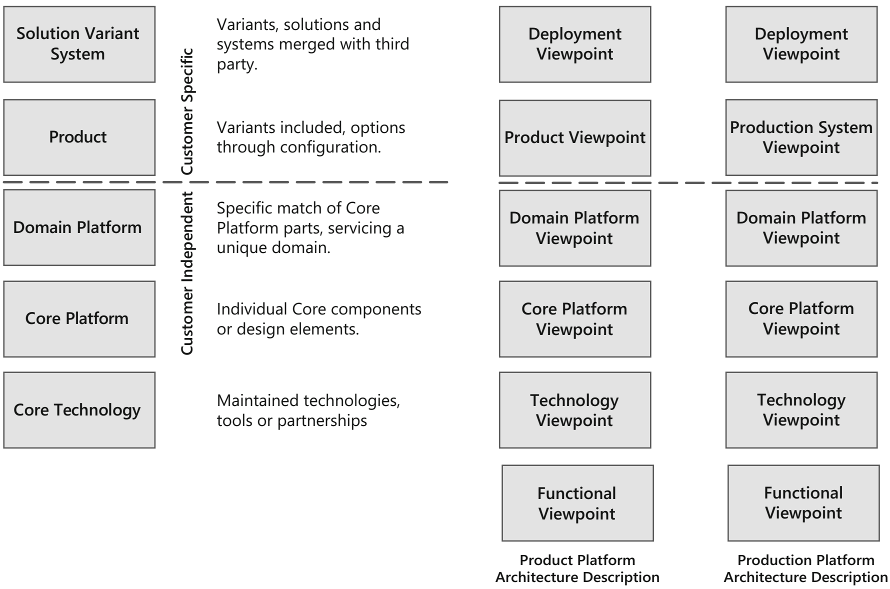

Fig. 2 Left: initial model, from one of the case companies, describing five viewpoints on a product. Right: reengineered model introducing “viewpoints” and covering both product and production platforms

views and a new functional view. Furthermore, the “solution variant system” has been replaced by a deployment view. Each side of the model represents the views for creating an architecture description of a product or production system based on a platform. Thus, the two sides of the model have been named product platform architecture description and production platform architecture description. The six views on each side constitute, for the sake of this paper, the architecture description, while the four views below the dashed line (functional, technology, core platform and domain platform) constitutes the platform description. Each of the views treats two essential questions in platform design in different context:

- What may change and what may not?
- Where is variety acceptable and desired and where is it not?

As the focus of this paper is on production platforms, the views related to this will be in focus in the following sections, but for the sake of explicitness, the views are explained briefly below.

- Functional view describes functional elements of the product or production system, their responsibilities, interfaces and primary interactions.
- Technology view describes fundamental technologies and how these are maintained and developed.
- Core platform view describes the library of components or design elements available in the platform and how these are maintained and developed.
- Domain platform view describes how core platforms are fitted to—but not limited to—an area of application.
- Product/production system view describes the results of internal development projects, i.e. a product or production system with one or more minor variants.
- Deployment view describes the deployment of the product or production system into its intended work environment.

In the following section, the FLC method for creating the four platform-related views is introduced.

3 Four Loops of Concern

In accordance with ISO 42010 [14], the creation or instantiation of a view is founded in its associated viewpoint. During this study a method utilising the concept of views and viewpoints was developed, dubbed the Four Loops of Concern (FLC) method. FLC is intended for guiding platform development in companies seeking to standardise tangible and intangible assets across product and production development.

At the current point in time, the maturity of this research is not at a state, where all viewpoints are formally defined, but rather at an explorative state, where the applicability of various models and methods are tested. It should thus be noted that both the method is still a work in progress and in need of further refinement.

In the following, the four viewpoints below the dashed line on Fig. 2 are represented through four development loops, each of which is dedicated to the instantiation of a single view by addressing a specific set of concerns. This is achieved by the creation of one or more artefacts (e.g. an instantiation of a model) individually addressing concerns and together constituting the view. Selection of the word "loop" for this method comes from the iterative nature of the development process, similar to the oft-used illustrations of software development processes through circles or spirals [18].

As exemplified by the brief description in Sect. 2.2, the concerns for each of the views are different, but the development loop for each view consists of the same four fundamental steps:

1. Gather (data collection) refers to the collection of data required to complete the loop.
2. Process (data processing) refers to methods, models and languages used to refine and structure data from step 1.
3. Evaluate (data synthesis) refers to evaluation and synthesis of information based on step 2.
4. Evolution (evolution track) refers to making a decision about the future of the artefacts created during the development loop.

These four steps, coupled with a loop for each of the four views, is what makes up the FLC method, as illustrated in Fig. 3. While each loop is dedicated to one set of concerns and one view, the methods and models used during the loop may be useful in other loops. The same kind, or even instance, of a model may very well be suitable for addressing different concerns.

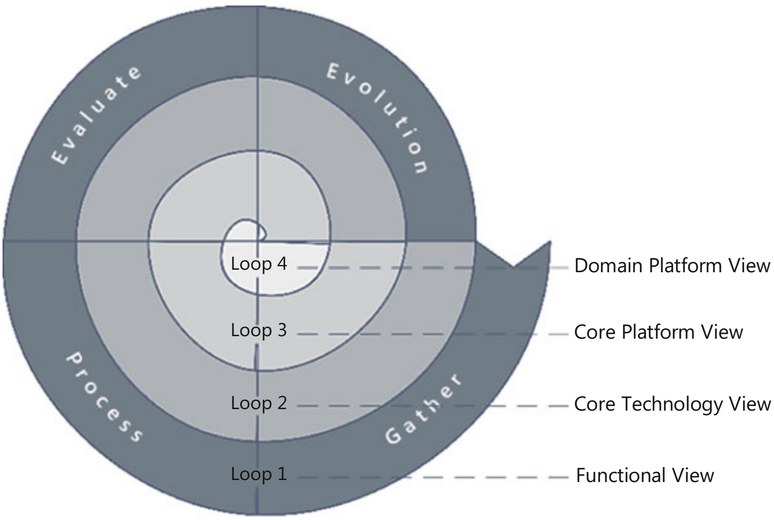

Fig. 3 The Four Loops of Concern method for development of platform descriptions

The word “system” is used to represent a production system in the following sections, where each of the four loops are explored in more detail, with respect to purpose, models, inputs and expected outputs.

3.1 Loop 1: Creating a Functional View

The functional view, as a cornerstone of a platform description, is intended to standardise intangible design elements in the functional domain [19]. It does so by defining the elements of a platform that deliver the system’s functional capability (i.e. functional elements), thus addressing concerns related to functional capability. By identifying the primary interactions between functional elements, it furthermore addresses concerns related to external interfaces and internal structure.

Data to support creation of the functional view is largely descriptive data, e.g. BOMs, production system layouts, product roadmaps, assembly drawings, etc. On-site inspection of systems and correspondences will greatly assist in gathering, as inherent knowledge of the system-of-interest is important.

The processing and evaluation step of this loop can be considered a so-called function reasoning process [20], capturing the function structure and rationale. Based on the gathered data, models such as process flows, function-mean trees [20] and functional modelling in general can be used to refine the data, facilitating comparison of systems to identify key design drivers and system characteristics.

The output from the process and evaluate steps of loop 1 should be an overview the scoped systems, their functions, main interactions, key design drivers and system characteristics with respect to, e.g. changeability [21], degree of automation and maturity. This can be illustrated in a matrix like shown in Table 1. The matrix above assists in identifying candidate functions for a platform, by providing an overview of how often and in which system functions are carried out. Design drivers provide some rationale on why a system is realised in that particular manner, and the interfaces outline main interactions in the system. All of this information is useful in the subsequent loops.

Table 1 Example matrix showing design drivers, functions and interfaces for production lines

				Line 1	Line 2	Line 3	…	Line 25	$\sum$
Design				DD1.1	DD2	DD3.1		DD25.1	
Drivers				DD1.2		DD1.1			
Functions	F1	F1.1	F1.1.1	1	0	1	…	0	18
			F1.1.2	0	1	0	…	1	5
		F1.2	F1.2.1	1	1	0	…	0	15
	F2	F2.1	F2.1.1	1	1	1	…	1	22
Interfaces			A–A	A1	A1	A2	…		–
			B–B		B1			B2	–
			C–C	C1				C1	–

Based on this overview, the goal of the evolution step is to make a decision on which functional elements to focus on during the subsequent loops and iterations. This should include both elements required by current systems and elements expected in the future.

3.2 Loop 2: Creating a Core Technology View

A technology is, for the purpose of this study, considered a solution principle [6], i.e. the basic principle of realising a function. The core technology view thus describes the solution principles available when designing a new system, addressing concerns related to development and maintenance of technologies.

Taking offset in the data and artefacts during loop 1, loop 2 largely focuses on decomposing the identified functional elements, as illustrated in Fig. 4. Through the process and evaluate steps, more detail is added by describing and illustrating the technologies. Conceptual and schematic drawings and are essential in this. For each functional element, at least one technology should be identified, for instance, by reusing the function-mean trees from loop 1 and mapping the results to a technology radar [22].

The output from loop 2 should, similar to loop 1, be an identification of which core technologies are available for use, which should be discontinued and new technologies expected to arrive in the future.

3.3 Loop 3: Creating a Core Platform View

Core platform is a term introduced by one of the case companies and describes how particular functional capabilities are carried out via means. Multiple combinations

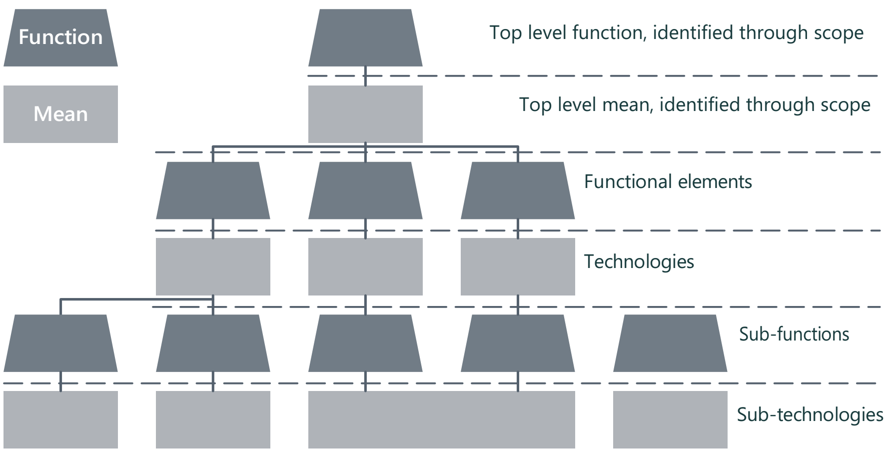

Fig. 4 Functional elements and technologies as a function-mean tree

of one function and several technologies may exist, leading to a variety of core platforms. A core platform may be the manner in which a particular joining function is realised through, e.g. laser welding or a number of screws. As such, the core platforms are the basic components, building blocks or modules from which the system is built. The purpose of this view is essentially to address the two questions listed in Sect. 2.2 and to address concerns related to development and maintenance of system elements, their interfaces and performance.

Through loops 1 and 2, all relevant functional elements and technologies are available. Loop 3 is then mainly a matter of system modularisation, grouping functional elements and technologies into modules. Various strategies can be employed for this, such as matching BOMs [23], modular function deployment and modular driver considerations in general [24]. While most data should be available through previous loops, additional data on performance and requirements may be required in order to compare the core platforms.

Based on the modularisation, the output of loop 3 is a set of core platforms that can be used in development of future systems, including their individual characteristics, performance parameters and interfaces.

3.4 Loop 4: Creating a Domain Platform View

The domain platform view contains models that describe specific matches of modules—coming from various system levels—to a given unique area of application. A domain is, for the purposes of this study, made up of a set of dimensions representing attributes strongly influencing the design and cost structure of modules—both individually in connection. By nature, these domains are case-specific due to the diverse system objectives for industries, companies, factories, etc.

To complete the fourth loop, all previous loops must be completed, and an appropriate number of domains must be defined. System stakeholders may have very different perspectives on what matters in development of systems, thus making the decision on which attributes to include in domains a difficult task.

Radar diagrams can be used to illustrate domains with agreed upon dimensions as shown in Fig. 5. A variety of concept and technical drawings are useful in describing the systems contained in the domains.

For each domain, at least one archetypical system should be created, i.e. the domain platform. This archetype is what future systems within that particular domain should be based upon. The domain platform should contain all applicable core platforms and their specific instantiation within the domain. If multiple domain platforms are necessary for a single domain, it should be considered whether the creation of a second domain is more appropriate.

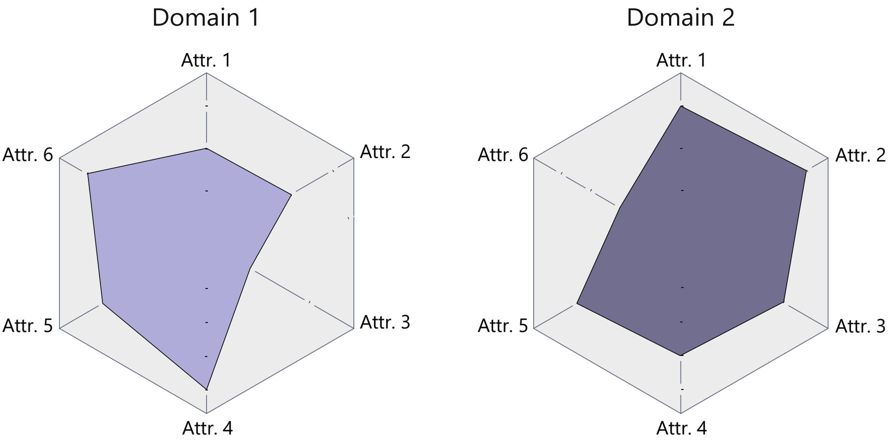

Fig. 5 Radar diagrams showing two domains spanning different dimensions on the same six attributes. Each domain represents a unique area of application

4 Case Studies

FLC was used in two separate case studies, each within their own context in separate companies. Each case study covered one production segment consisting of multiple production systems, cells and stations [17] in their respective company. One being a large enterprise with high volume and high variety (case study 1, CS1) and another being a small-medium enterprise with low volume and high variety (case study 2, CS2). Products manufactured in CS1 were relatively small control boxes, while products covered in CS2 were comparatively large welded components. CS1 had a relatively high degree of automation, ranging from manual to semi- and fully automated, with CS2 having a comparatively low degree of automation, being primarily manual or semiautomated.

Both case studies had a duration of 20 weeks. For CS1, the project group initially consisted of 20 people from various departments, each with their own field of expertise. Joint meetings and workshops were held once a week to encourage codevelopment and collaboration between product and production engineering stakeholders. CS2 involved two people, meeting 1–2 days per week for the same 20 weeks as CS1. During both case studies, additional experts were involved when necessary. Participants in both case studies worked more or less on their own with varying intensity between the weekly meetings, as other tasks within the companies were still ongoing.

The data used in both case studies came from expert (system VIP) opinions, ERP system and practical data collection at production lines. These two companies were deemed appropriate cases because of the variety of products manufactured by the companies and the difference between the two companies in terms of size, products and strategy.

4.1 Scope

Simultaneously with the activities described by the FLC method, the platforming process of CS1 was scoped through what was dubbed a "holistic overview". The holistic overview included data on which systems were covered by the platforming project, their nature, performance, structure and initial comparisons of the systems. Furthermore, the holistic overview included data on all the products being manufactured on the scoped systems. This resulted in a scope covering 23 production systems and 25 physically different product architectures. Additional firmware and software variants exist, but only physically different architectures are considered. Ideally, the scoping process should be carried out prior to initiation of the FLC, but this was not possible for CS1.

CS2 was scoped by clustering components based on similar routes and process commonality [25]. The resulting scope covered one production system and 84 components with physically different product architectures.

4.2 Implications

After applying FLC in both case studies, a number of views, consisting of one or more documents, were created. These views were collected in two books—one for each company. The books each represent the first iteration of a collection of platform descriptions for the scoped products and production systems within each company. Not all elements (functional elements, technologies and core platforms) identified through the loops are covered in detail in the books. Instead they are briefly described, with a few elements described in detail, along with specification of domains and guiding principles for future development of the books and the platforms themselves.

Due to the subjective nature of functions and their granularity level [17], it is challenging to identify the functional commonality across production systems. This, along with a lack of classification scheme for production processes, resulted in vastly different results when two different individuals mapped the same production system. To accommodate this, and make the results comparable, function-mean trees were used but proved too exhaustive for physical data collection. Instead, function-mean trees were used in conjunction with expert opinions and knowledge from production system VIPs. Design drivers and system characteristics were likewise based on expert opinions, since no suitable, quantifiable indicator metrics were available. In fact, much of the data collected and documented during the case studies were based on expert opinions, as one of the purposes of platform development and documentation is to document the tacit knowledge held by stakeholders and experts.

The mindset needed for thinking in principles rather than immediately progressing to physical concepts and solutions was difficult for participants in CS2. Tacit knowledge was available from the expert participants, but although the concept of describing principles over physical solutions was understood to some degree, some experts had some scepticism as why the subject was of interest. Concerns were raised that the case study was an attempt at highlighting bad decisions in the past, while the opposite was the intent—highlighting good solution principles for future development.

Communication of the, to the companies and participants, new concepts and constructs from ISO 42010 and platform development in general proved challenging. While the concepts were used as a backbone for the development process, the introduction of parts of the new vocabulary, e.g. the use of views and viewpoints, was dismissed relatively quickly.

While the vocabulary was a challenge, the FLC method was successful in guiding and assisting the process of documenting both tacit and explicit knowledge. It further assisted in identifying solution principles to continue developing and principles to be discontinued based on their performance.

5 Discussion

Through this study, an attempt was made at employing concepts and constructs from software architecture development, to create a method for develop of production platforms. The case studies showed that the mindset of system stakeholders is not necessarily ready for this type of design thinking.

After the dismissal of the vocabulary, alternative viewpoints and views have been explored. Adoption of viewpoints that align well with the development process the developers are familiar with, and are more easily relatable to physical objects, may be beneficial, for instance, the RFLP views (Requirements, Functional, Logical, Physical) used by Dassault Systèmes [26].

A classification of production processes, including manufacturing, handling and test, is the subject of future study. Such a classification scheme would benefit the mapping process greatly, forming a common ground for function granularity, and assist in the identification and grouping of modules based on functional commonality.

Characteristics of the production systems were compared qualitatively to each other, in order to identify the relative performance of the systems in terms of, e.g. changeability, etc. This comparison would greatly benefit from more quantifiable measures, as the characteristics are currently more theoretically than practically defined.

A key step in further development of the FLC is the refinement of individual viewpoints. In order to make each viewpoint usable outside of the two case studies, they should be formally defined. One starting point for such a task is the specification in ISO 42010. According to this, a viewpoint should specify: (1) framed concerns, (2) stakeholders for each concern, (3) model kinds, (4) languages and conventions for each model kind and (5) relevant references. The methods and models briefly outlined in Sect. 3, along with alternatives, should be applied to a wider array of systems to strengthen the foundation of FLC and viewpoint specification. As development progresses, fundamental changes or a need for additional viewpoints may appear.

In summation, the Four Loops of Concern method for creating platform descriptions uses standardisation of intangible elements—i.e. functions and solution principles from loop 1 and 2—as a means for creating consistency and decreasing variety of system design elements, i.e. core and domain platforms in loop 3 and 4.

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Integrate Customer Order Decoupling Point and Mass Customisation Concepts: A Literature Review

Violetta Giada Cannas, Margherita Pero, Tommaso Rossi, and Jonathan Gosling

Abstract The postponement represents the key strategy for companies to achieve mass customisation. It is associated with the customer order decoupling point (CODP) positioning: the backward shifting, from a pure standardised configuration (i.e. make-to-stock (MTS)), allows companies to delay some supply chain activities until the customer order arrives, increasing product variety while maintaining efficiency. This concept has been widely analysed in the literature, but there is a lack of studies about the means to reach more standardisation starting from a pure customised configuration (i.e. engineer-to-order (ETO)). Nevertheless, the movement toward mass customisation benefits also ETO companies, by reducing costs and lead times while assuring flexibility, and represents a need in the high-competitive global markets. Therefore, this concept needs to be extended to a wider perspective that includes possible levels of customisation achievable from different configurations. This is possible through a good understanding of the CODP theory. This paper reviews the CODP literature to investigate the different existing perspectives and classify them in a structured framework. This framework compares the CODP literature with the mass customisation one, to understand what are the interconnections among them in the actual state of the art and what is missing to achieve a more general view of these concepts. This allows the study to open further research highlighting the recent trends and the uncovered topics.

Keywords Customer order decoupling point · Mass customisation · Postponement · Engineer-to-order

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1 Introduction

The mass customisation (MC) strategy has been strongly recommended by academics and practitioners over the last three decades. This strategy allows companies to provide customised products at the efficiency of mass production [5] and supports them in facing the increasing demand for variety and the growing competition in the global markets. The practical application of MC is associated with the postponement strategy [50], which has been associated to two main meanings in the literature [12]: (i) the most utilised and traditional applies a "pure standardisation perspective" (i.e. from the make-to-stock, MTS, configuration to MC), aiming at delaying as much production activities as possible, until the customer order arrives, to increase variety; (ii) the less common and more recent applies a "pure customisation perspective" (i.e. from the engineer-to-order, ETO, configuration, to MC), aiming at postponing the product differentiation closer to the time of delivery, to increase efficiency. In both cases, companies applying postponement should define with maximum attention and accuracy what activities must be based on forecast and what on customisation [49]. This makes the postponement concept strongly connected to the customer order decoupling point (CODP) [41], i.e. the point where the customer order occurs, differentiating the activities driven by speculation from the ones driven by customisation [19]. Consequently, the location of the CODP represents a strategic and important choice for companies, but this concept is not completely clear in the literature, and the interpretations are different based on the perspective of the study.

The traditional CODP definition, related to the pure standardisation perspective, takes mainly into account a production dimension (PD) point of view, referring the concept to the main stock point along a continuum of production activities, i.e. manufacturing, assembly and delivery. This view rarely included the engineering phase and distinguished it from the production ones; in the rare cases where this happened, the two dimensions have been analysed as sequential, never overlapped and integrated one with the other. Despite the engineering dimension (ED) did not receive the same attention as the PD in the CODP literature, recent reviews increasingly underlined the importance of its interface with the production one. Dekkers et al. [8] stated that this integration makes the CODP concept suitable to different industries, including the peculiar ETO context. In particular, the two-dimensional CODP (2D-CODP) framework presented by [45] has been underlined in the literature as a good starting point to represent this ED-PD integration [14]. This innovative framework considers the possibility to choose different customisation levels within both the ED and PD and correlates the engineering resources with the operational process [45], anticipating PD constraints in the early phases of the product development [33]. This makes the CODP suitable for different contexts (i.e. both high standardised and high customised) and can help in describing several MC situations not covered by the existing literature. Thus, there is a need to better understand the topic and find the possible interconnections with the MC concept. While the MC and postponement concepts received high attention in the literature, as far as we are aware, there are no systematic literature reviews on the CODP and its correlations with MC (Fig. 1).

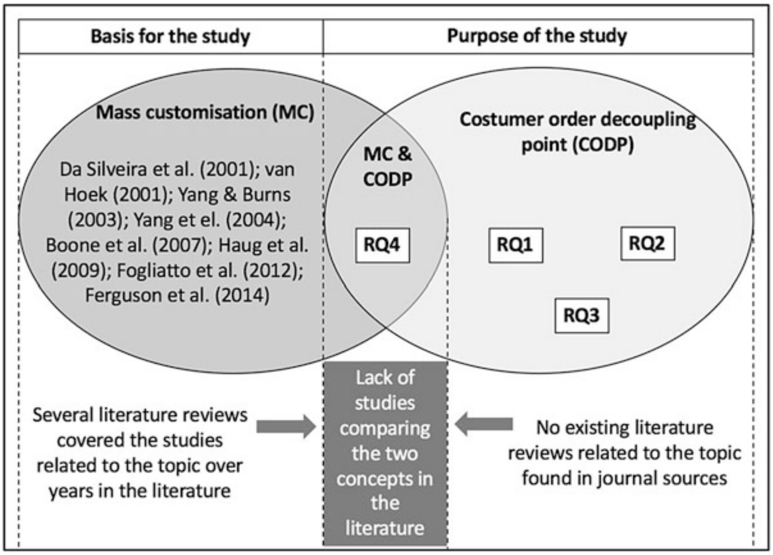

Fig. 1 Purpose of the study

Therefore, this paper presents a literature review on the CODP concept, aiming at structuring the evolution of the CODP theory over years, underlying what has been done and what needs to be done, especially looking at the new two-dimensional perspective. This can help researchers and practitioners to organise the existent knowledge related to the topic, clarify the different views and identify recent trends and uncovered issues. Then, an application of the 2D-CODP concept to the existing MC typologies identifying in the existing literature is shown. This application is useful to clarify that the strong interconnections of the two topics is useful to achieve a broad and comprehensive perspective applicable to the modern industrial contexts. Finally, a structured framework is provided, with new interesting research questions, and opens further research, based on the main gaps found in this study.

The main objective of the study, according to what stated above, is to understand the following points:

- The existent definitions of the CODP and the different possible configurations provided by the literature along the continuum of activities in both production and, when considered, engineering dimension
- The tools to manage the forecast-based and customer order-based activities, to find the optimal balance among them when the CODP is located between pure standardised and pure customised configurations
- The managerial implications of the choice of a certain CODP position, to choose the right level of customisation based on the factors characterising the context where the company operates

- The connections among the 2D-CODP and the MC concept analysed in the literature over years, to understand how the 2D-CODP framework helps in classifying different possible MC configurations

Accordingly, the research aims at answering to the following research questions (RQs), underling the main gaps existent in the literature:

- RQ1: What is the CODP and its possible configurations in the continuum of activities?
- RQ2: How does a company manage the activities upstream to and downstream from the CODP?
- RQ3: Why does a company should shift the CODP backward or forward?
- RQ4: What are the main connections among the 2D-CODP and the MC configurations?

In Fig. 1 the basis for the study and the main purpose, together with the RQs, are shown.

The paper is structured as follows: Section 2 describes in detail the research methodology; the main findings about the CODP literature review are provided in Sect. 3; the existing literature about MC is discussed in Sect. 4 and compared with the results of the CODP literature in Sect. 5; finally, Sect. 6 concludes the paper providing the final discussion and showing the resulting research framework, which opens new research questions for further research.

2 Research Methodology

The literature review was structured in the following steps, according to Cronin et al. [4]: (i) literature searching, (ii) reading and analysis of the literature and (iii) review of the literature.

The main scope of the literature searching (i) was to identify a complete list of valuable studies related to the area of investigation by following a systematic method [3]. The strategy followed in this paper consists in including both empirical and theoretical works, to consider the actual state of the art in terms of conceptualisation, but also the actual practical problems and issues. The time frame of the research, within which the literature was selected and read, starts from the seminal paper to date, since the objective is to analyse and study the evolution of the CODP concept over years. The path followed in this phase is the screening of publications (i.e. scientific journal articles) on two main sources, database of peer-reviewed literature (i.e. Scopus, Web of Science) and the use of a science search engine (i.e. Google Scholar) to support the document searching. The papers are selected based on specific keywords related to the area of investigation, namely, “customer order decoupling point” (OR), “order penetration point” (OR), “order entry point” (OR) and “order fulfilment point”. The keywords chosen are alternative (i.e. Boolean operator “OR”) to obtain as much information as possible related to the topic [4]. This first step has generated a list of 3663 articles from Web of Science and 4988 papers from Scopus. Moreover, a set of filters was applied to the search based on the “subject area”, excluding the areas not related to the industrial engineering, management and economics (e.g. “medicine”, “veterinary”, “neuroscience”, etc.), and the “language”, including only papers written in English language. The choice is to include all the possible source types, i.e. journal articles, conference proceedings and books to have the highest possible overview about the existing knowledge related to the topic. The combination of keywords and the application of a set of filters proposed by the database have generated a list of 283 articles from Web of Science and 430 articles from Scopus.

The second step (ii) consisted in the reading and analysis of the titles and the abstract of the publications, to understand the main contents and to support another inclusion or exclusion process as suggested by [4]. The strategy followed to elect a publication as worthy of further readings, according to [3], is based on the relation of the contents with the main purposes of the study explained in the previous section. Thus, the lists of articles obtained from the previous phase have been crossed and screened, and, in total, 39 papers have been selected to be the starting point for the full-text reading and the review phase.

The review of the literature (iii) structures the knowledge on the topic, defining the relationships among the different studies and understanding how the topic is changed and developed over the years. The selected articles were analysed through a full-text reading and classified trying to answer to the main research questions defined in the previous section. Consequently, they were categorised as “what”, “how” and “why”. The “what” perspective has the main purpose to answer the first research question (RQ1) by defining the interpretation given to the CODP concept and the different configurations of CODPs derived from this interpretation. The “how” perspective is instead related to the second research question (RQ2) by addressing the analysis of the management and control systems related to the location of the CODP. The “why” perspective is related to the studies that look at the CODP concept under a strategic perspective, answering the third research questions (RQ3) by identifying the main reasons and implications related to the CODP shifting. In the following subsections, each of these dimensions is analysed in-depth with respect to the contributions. Finally, the results of the literature review were compared with the existing literature related to MC, widely analysed by several studies. In particular, this analysis started with the comparison with the “what, how and why” of MC introduced by [25]. These perspectives were explained by looking at the several existing reviews on the topic, which already structured effectively the existing literature. This comparison with the MC literature supports the searching for all the possible interconnections among 2D-CODP and MC, answering to the fourth research question (RQ4).

The steps described above are summarised and shown in Fig. 2.

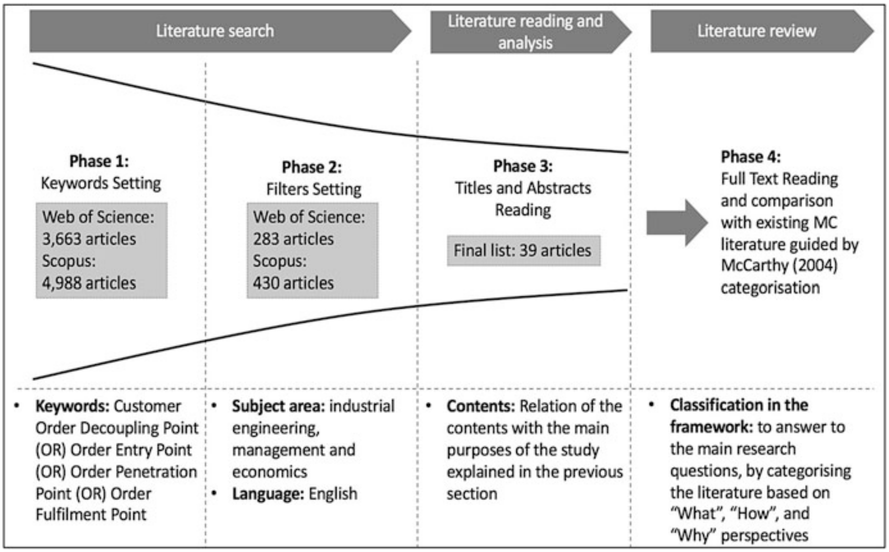

Fig. 2 The literature review methodology

3 The Customer Order Decoupling Point: What, How and Why

3.1 Descriptive Analysis

Table 1 shows the classification of the papers reviewed based on (i) their relationship with the PD and ED; (ii) the specific area to which they gave the main contribution, among the "what", "how" and "why" perspectives; and (iii) the research methodology applied to the study.

Table 1 shows clearly the main research outcomes of the literature review. It is straightforward that most of the studies are related to the PD CODP, while still few studies addressed the ED CODP and its correlation with the PD CODP. Moreover, the analysis points out that each perspective has been studied in the literature with different methodologies. The conceptualisation has been the method mostly used to analyse the "what" and "how" perspectives, while the qualitative methodologies have been mainly used to explore the "how" perspective; finally, the quantitative methods have been principally related to the "why" perspective.

Some articles addressed the ED CODP topic in literature in correlation with the PD CODP, providing new interesting frameworks and suggesting new directions for further researches; but, there is a lack of empirical contribution to the topic. Moreover, no works have been developed in this direction since 2006. But, although this shortage of contributions, the importance of a better understanding related to the ED CODP and its relationship with the PD CODP has been strongly underlined by

Table 1 Literature review classification and results

Genreral methodology	In-depth methodology	References	What		How		Why	
			PD	ED-PD	PD	ED-PD	PD	ED-PD
Conceptual		Sharman (1984)	X				X	
		Wortmann (1992)	X					
		Hoekstra and Romme (1992)	X				X	
		Giesberts and van der Tang (1992)		X				
		Lampel and Mintzberg (1996)			X			
		Porter et al. (1999)		X				
		Olhager (2003)	X				X	
		Rudberg and Wikner (2004)		X		X		X
		Wikner and Rudberg (2005a)		X		X		X
		Hallgren & Olhager (2006)			X			
Qualitative	Multiple case studies	Amaro et al. (1999)		X				
		Mason-Jones et al. (2000b)			X			
		Dekkers (2006)		X		X		X
		van Donk & van Doorne (2016)			X			
	Single case study	van der Vlist et al. (1997)			X			
		Naylor et al. (1999)			X			
		Mason-Jones et al. (2000a)			X			
		Van Donk (2001)					X	
		Wikner and Rudberg (2005b)	X					
		Verdouw et al. (2008)	X					
		Risdiyono and Koomsap (2013)					X	

(continued)

Table 1 (continued)

Genreral methodology	In-depth methodology	References	What		How		Why	
			PD	ED-PD	PD	ED-PD	PD	ED-PD
Quantitative	Optimization model	Sun et al. (2008)					X	
		Fahmy et al. (2015)					X	
		Liu et al. (2015)					X	
		Liu et al. (2016)					X	
	Simulation study	Mason-Jones and Towill (1999)	X					
		Viswanadham and Raghavan (2000)					X	
		Wikner et al. (2007)			X			
		Hedenstierna & Ng (2011)					X	
		Daaboul et al. (2015)						X
		Okongwu et al. (2016)					X	
		Wang & Chen (2016)					X	
	Optimization model and simulation study	Daaboul et al. (2010)					X	
Hybrid methods	Case study and survey	Olhager (2010)			X			
	Case study and focus group	Gosling et al. (2017)		X				

recent works as, for instance, [8, 14]; together with the relevance of the development and in-depth exploration of 2D-CODP frameworks such as the ones developed by [7, 32, 45].

3.2 What

The CODP concept is traditionally defined as the point in the material flow where the customer order arrives [13, 19, 35, 48]. Thus, based on the CODP location, it is possible to identify the activities driven by speculations from the activities oriented toward specific customer requirements. In this sense, the CODP represents the main strategic buffer in the materials pipeline where the flow of activities changes from push to pull conditions [16, 18, 22, 24, 29–31, 36, 39, 40, 43].

According to Wortmann [48], there are four main different CODP configurations that can help in classifying the manufacturing systems. The configurations, shown in Fig. 3, are mainly four: (i) ETO, all the activities completely based on customisation; (ii) make-to-order (MTO), production and assembly activities completely based on customer orders, while the engineering activities are based on speculation; (iii) assemble-to-order (ATO), based on a hybrid approach where the engineering and production activities upstream to the CODP are standardised and based on forecast, and the assembly activities downstream from the CODP are customised; and (iv) make-to-stock (MTS), all the activities completely based on speculation.

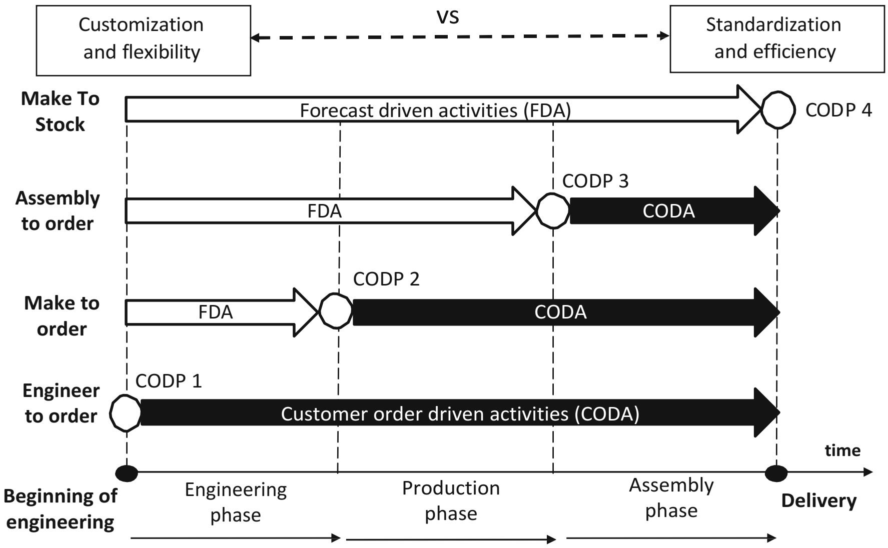

Fig. 3 Manufacturing systems configuration based on different CODP positions [48]

In the literature, not all the researchers agree on the interpretation of the engineering phase and the ETO configuration. Few authors considered the engineering phase as separated from the production phase, maintaining the ETO configuration, for example, [30, 42, 46], while the majority excluded the engineering phase, for example, [13, 16, 18, 23, 27, 36, 39, 40, 47], because the traditional definition of the CODP is related to the PD, making the distinction among ETO and MTO not relevant from a material flow perspective [16].

This definition of the engineering phase was criticised in literature for its very broad meaning first by [1, 31]. They preferred to better detail the different phases related to the ED, taking into account different levels of customisation, distinguishing engineering activities performed to create a completely new design from the ones that adapt an existing design on a specific customer order. In this sense, Porter [31] add different dimensions in the ED, distinguishing design-to-order (DTO), where the product design is completely based on an individual customer order, from ETO, where a standard product range is offered to the customer and modifications are made to request. Furthermore, Wikner and Rudberg [45] and Rudberg and Wikner [32] criticised the traditional sequential approach adopted by CODP literature, which does not differ the PD from the ED. Since the increasing competitive pressure in the markets requires companies to anticipate some production activities acting in combination with the engineering ones, there is a need for a specific framework that considers this possibility to overlap and correlate the ED with the PD. Thus, they specified a new CODP concept related to two dimensions: both PD and ED. They identified six possible CODP configurations: three configurations are related to the PD and consist of the already defined MTO, ATO and MTS, while the other three configurations are related to the ED – (i) ETO_{ED}, product designed from scratch; (ii) adapt-to-order (ATO_{ED}), existing designs adapted based on customer order; and (iii) engineer-to-stock (ETS_{ED}), product design already "in stock". Dekkers [7] defined a 2D-CODP based on the PD CODP positioned along the traditional material flow and the ED CODP located along the information flow. This second CODP depicts the degree of transformation of product specifications into a detailed product design and production ramp-up. Accordingly, there are four different ED CODP configurations: (i) no engineering activities needed and the production ramp-up is already done; (ii) the design of the product is already defined but the production ramp-up is necessary; (iii) adaptations to the existing product design are needed; and (iv) the product design needs to be completely defined. This new 2D approach makes the CODP suitable to classify not only manufacturing systems but also different types of engineering activities; this is good especially for companies that perform engineering adaptations through the balance of forecasting, based on the past and also the future design needs, and customised activities, based on the specific customer order [32]. Recently, Gosling et al. [15] addressed the empirical study of the CODP concept applied to the engineering activities. They developed a conceptual framework composed by nine potential ED CODP configurations that allow researchers and practitioners to classify the different degrees of customer involvement in the ED. Despite the relevance of this framework, the authors stated that a wider investigation in different

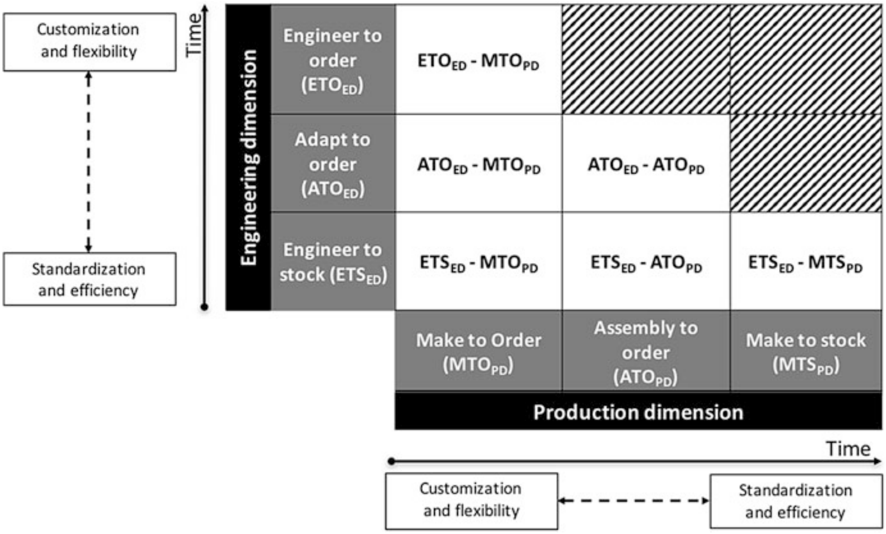

Fig. 4 Configuration based on different 2D-CODP positions [45]

sectors is needed to increase the findings generalisability. Also, the decision-making process that defines the positioning in the different possible CODP configurations needs more in-depth studies.

The 2D-CODP configurations are represented in Fig. 4.

3.3 How

The literature supports the idea that different approaches are needed to manage the activities upstream to and downstream from the CODP [38, 46, 47], since they are led by distinctive drivers, i.e. forecasts vs customer orders [16, 30]. The purpose before the CODP is to control the activities and guarantee maximum internal efficiency, while after the CODP the focus is on satisfying the customer order at the maximum flexibility and at the minimum lead time [7, 42].

Accordingly, the literature suggests two different strategies based on the priorities that the company has in the PD: (i) the lean strategy upstream to the CODP, to reduce all the wastes along the value stream, including time, and (ii) the agile strategy downstream from the CODP, to reach maximum responsiveness for customised and innovative products with unpredictable demand and short life cycle [27]. Thus, the lean approach supports the forecasting-based mechanisms, while the agile approach the fulfilment-related mechanisms [40]. In order to handle the efficiency-flexibility trade-off, the literature suggested to balance the lean and agile strategies by means of the strategic use of the CODP through "leagile" paradigm. This concept was first introduced by [27] that defined the lean and agile approaches as two complementary paradigms instead of unique or sequential along the supply chain. The good combination of these two paradigms by the "leagile" strategy helps to find efficiently a high level of responsiveness [46].

These strategies are related to the PD, but [45] stated that they could be appropriate for the ED where the flexibility-efficiency trade-off also needs to be balanced. [7] stated that this trade-off consists in assuring a good balance among the design customisation and design reutilisation in the ED. But a more in-depth analysis is needed in terms of management and control strategies related to the activities performed before and after the ED CODP [8].

3.4 Why

Traditionally, the CODP positioning is associated with the balance among service level (i.e. companies' ability to satisfy market requirements assuring delivery reliability in terms of LT, flexibility and stock availability) and costs (i.e. companies' ability to minimise inventory costs caused by stock holding, stock obsolescence or stock deteriorations) [23, 35, 43]. CODP positioning aims to reach stock reduction and improve flexibility, in accordance with the customer delivery LT [38]. Therefore, CODP positioning is considered a strategic decision that depends on several different drivers and affects lead-time performance [29].

According to Sharman [35], CODP positioning is driven by competitive pressure, leverage within the distribution chain and product cost and complexity. Then, Hoekstra and Romme [19] defined CODP positioning as based on the balance of market requirements and process characteristics. The main driver identified in this sense is the P:D ratio, where P is the production lead time (i.e. the time needed to realise the product along the value-added material flow) and D is the delivery lead time (i.e. the time that a customer is willing to wait). Given this ratio, if P is longer than D, CODP should be shifted downstream to answer effectively to the market requirements. Olhager [29], starting from previous works, defined a "conceptual impact model factor" related to CODP positioning, to support manufacturing companies in choosing the right product delivery strategy based on P:D ratio and the factors affecting it. [29] defined three main factors that affect the positioning: (i) market-related factors, related to all exogenous factors pushing companies in some measures to standardise or customise products (e.g. product demand volatility, product range and product customisation requirements, etc.); (ii) product-related factors, related to the product features (e.g. modular product design, customisation opportunities, etc.); and (iii) production-related factors, related to production process (e.g. production lead time, planning points, etc.). Even if [29] study is an optimal base to identify proper product delivery strategy, it is focused only on PD, and most of the following articles based their studies on this traditional perspective, for example, [16, 18, 20, 28, 30, 36, 42, 44, 46, 47].

Wikner and Rudberg [45] defined the 2D-CODP positioning as based on the relationship among the LT required by the customer and the engineering and production total LT; in addition, they also considered the possibility to overlap ED-PD, considering the sum of engineering and production LTs as affected by a "delta value" (i.e. the slack time between engineering and production). This "delta value" could be zero if they are sequential or negative if they are overlapped [45]. Furthermore, Dekkers [7] stated that upstream shift of the ED CODP improve the flexibility with respect to customer requirements, while the downstream shift of the ED CODP enhances the possibility to reuse existing product designs, diminishing engineering costs and LTs. Recently, Daaboul [6] analysed the simultaneous positioning of the CODP and the PDP (product differentiation point, i.e. the point in which the product design changes from standard to personalised) by performing a simulation study. They stated that these two dimensions should be not considered as exclusive alternatives. Therefore, the PDP and CODP positioning, namely, the variety creation and implementation, should be defined following an integrated decision-making approach that considers the impact on costs, lead times and quality level of the whole supply chain processes. This makes possible to well apply MC, reaching a global value optimisation, not only for the manufacturer but also for all supply chain stakeholders (i.e. customers, suppliers, etc.).

4 The Mass Customisation Strategy: What, How and Why

McCarthy [25] analysed the MC concept from a what, why and how point of view, looking at the existent literature and opening further research in the topic few covered but relevant for this field:

- The what dimension is referred to the definition of MC, traditionally described in the literature as the ability to provide a large number of customers with customised products that satisfy their individual needs [9, 34]. [25] stated that the traditional MC viewpoint excludes companies that realise products in low volumes, referring MC to the ATO_{PD} configuration reached from a MTS_{PD} one. This is a limited perspective; the approaches to the MC can involve different companies' typologies and can be classified in different ways based on the companies' need.
- The how dimension is related to the possible configurations to apply to the manufacturing systems in order to support MC. Among them [25] distinguishes flexibility, postponement, modularity, information technology and CODP positioning. Therefore, in this dimension, the possible CODP configurations (what CODP dimension) and the strategies for the positioning (why CODP dimension) are considered key aspects.
- The why dimension is related to the main reasons for the application of a MC strategy and the consequent implications. In this sense, [25] defined the reasons as mainly based on competitive factors: the capacity to satisfy the market need

for variety, the possibility to handle the shortening of the product life cycles and fast shifting in customer preferences and the opportunity to maintain good performance in the process in terms of costs, quality and delivery, while the implications have been defined as the challenging task of reducing or eliminating the performance trade-off among efficiency and flexibility in the production process.

In the literature, several models conceptualise the MC configurations over years, analysing the what, how and why perspectives. As for the CODP, in the MC literature the broad perspective is still not very considered in the what, how and why dimensions, since the principal way to achieve MC has been related to the traditional postponement, i.e. backward shifting of the CODP: defined as the method to achieve MC, by delaying the activities as latest possible, waiting for the customer order to arrive and specifying the desired product attributes [50], while very little attention received the other interpretation of postponement provided by [12, 17], i.e. the forward shifting of the CODP: method to achieve MC, by moving the differentiation point closer to the market and the time of delivery, increasing the design standardisation and anticipating production activities [12]. In the following, models that consider different possible levels of customisation are analysed.

Mintzberg [26] defined different possible customisation strategies based on when the customer is involved in the process, including the possibility to act in both the design and the production process: (i) design phase, with pure customisation based on specific customer order; (ii) fabrication phase, with tailored customisation based on the modification of basic standard design based on the customer order; (iii) assembly phase, with standard customisation based on different combination of standard components; and (iv) delivery phase, with pure standardisation based completely on forecast. Amaro et al. [1] analysed mass customisation in non-MTS context to understand the new taxonomies needed in these peculiar contexts where customisation is one of the main competitive advantages. He noticed that in the traditional interpretation of MC provided by Pine [34], the only MC view included was the one defined by [26] as standard customisation, while all the other configurations were not considered. Through an empirical investigation, [1] demonstrated that pure customised companies also apply MC strategies, by improving standardisation within their internal engineering and production processes. They affirmed that when the MC concept is applied to non-MTS companies, the reasoning and implications of the application of this approach should include the improving of internal capabilities also in the engineering process. Duray [10] defines the MC as strictly related to the customer involvement in the production cycle and modularity type. This allows to consider different possible MC configurations based on the positioning of the customer involvement in both the engineering and the production processes. The framework developed is a matrix which classifies mass customizers based on the different points of customer involvement proposed by [26] and the different types of modularity provided by Ulrich and Tung [37]. The latter are based on the moment when modularity is applied: in the design or fabrication phase, modularity is capable to modify the components, and the design customisation degree is still high; in the assembly or delivery phase, modularity is capable to add or interchange modules, without modifying them. The mass customizers' typologies identified in this matrix are four: (i) "fabricators", with both customer involvement and modularity at the design/fabrication phase; (ii) "involvers", with the customer involved since the design/fabrication phase, but the modularity at the assembly/delivery phase; (iii) "modularizers", with the customer involved only at the assembly/delivery phase, but the modularity applied at the design/fabrication phase; and (iv) "assemblers", with both customer involvement and modularity at the assembly/delivery phase. Salvador et al. [51] proposed a systemic view of MC, considering product design, marketing, sourcing and manufacturing. They performed an empirical study and identified two different MC typologies: soft and hard. To define different MC typologies, they integrated the modularity type to the supply chain configuration, looking at the customer, the distribution, supply and manufacturing network. The soft MC is defined as the supply chain configuration able to reach high efficiency in terms of economies of scale and scope while providing moderate levels of customisation through component modularity that affect only a small part of the SC. In this configuration customers are served on MTS basis, but the manufacturing and supply processes are able to manage a little level of customisation. The hard MC is defined as the supply chain configuration where customers ask for more customisation but are willing to pay and wait more. In this case, the modularity applied is combinatorial and extensive, involving the entire supply chain that needs a strong interaction among engineering and production activities. In this configuration, the customers are served on MTO/ATO basis, and the manufacturing and supply processes have a strong interaction with the engineering one, able to manage high levels of customisation.

5 Integration of MC and CODP Concepts

All the contributions analysed in the previous section underlined the importance of the inclusion and extension of the ED concept, in correlation with the PD, within the MC, postponement and CODP theories, and the need for more studies related to these field. This PD-ED integration is one point analysed in the literature since the beginning of the MC studies and supported by following studies.

Boone et al. [2] stated that one of the open challenges in the field is to extend MC concept, including the product design process together with the production one, to understand the possible different points until companies can postpone activities with a complete view of the supply chain. Gosling and Naim [14] identified a lack of studies related to the possible strategies to forward shift the CODP from ETO configurations, suggesting the use of modularity to manage the high variety of the context and highlighting the need for more studies about the application of postponement in the design phase. Haug et al. [17] agreed that more efforts should be put in the literature to define MC: on the one hand, by extending the concept to a broader meaning, including the ETO perspective, and, on the other hand, by identifying all the different levels that companies can reach along the continuum of activities from pure customisation to pure standardisation. MacCarthy [21] underlined that there is a continuum of approaches that companies can apply to fulfil the customer requirements for variety and customisation, based on the sector where they operate and changes that affect it over time. These approaches include product design as well as manufacturing aspects in a new integrated perspective that is suitable for different types of industrial sectors. Also, Ferguson et al. [11] underlined the dependency of the successful application of MC to the decision-making in the product development process and provided a product development framework to help in minimising the trade-off among the ideal product design required by the customer and the one available in the company's design solutions.

The importance of the PD-ED integration is straightforward if we try to cross the MC, postponement and CODP frameworks developed over years. In Fig. 5 an attempt of this integration is presented. The pure standardisation view is depicted as a one-dimensional CODP framework, as the one proposed by [19, 48], where the MC configuration is obtained, thanks to the backward shifting from MTS to ATO configuration, as defined by [9, 34]. The pure customisation perspective is depicted as a one-dimensional CODP framework where different customisation configurations are added in the engineering phase, distinguishing DTO and ETO as proposed by [31], and MC is achieved by a forward shifting from pure standardisation to tailored or standard customisation, as proposed by [1, 26]. Finally, the general and broad perspective is depicted as a 2D-CODP, as the one proposed by [45], where the CODP shifting is possible in different directions and from different engineering and production configurations. The different possible MC configurations can be, for example, the ones proposed by [10] and [51] that can be inserted easily and consistently in the 2D-CODP framework.

It is clear from Fig. 5 how the pure standardisation and pure customisation perspectives are limited with respect to the general and broad one, where different strategies can be applied to the shifting from a specific industrial context to different customisation levels. This confirms the importance of further research, conceptual and empirical, to the topic to reach the broad perspective needed in the literature.

6 Discussion and Conclusions

In conclusion, the literature review emphasises important gaps that open interesting spaces for further research. The framework provided in Fig. 6 shows the main results obtained from the CODP and MC literature reviews and the cross analysis of their contents. Everything is explained and discussed below.

About the first research question (RQ1), "What is the CODP and its possible configurations in the continuum of activities?", the existent knowledge agrees on the general conceptualisation of the CODP that is defined as the point at which the customer order arrives and its requirements become the driver of the flow of activities that adds value to the final product/service realised within the

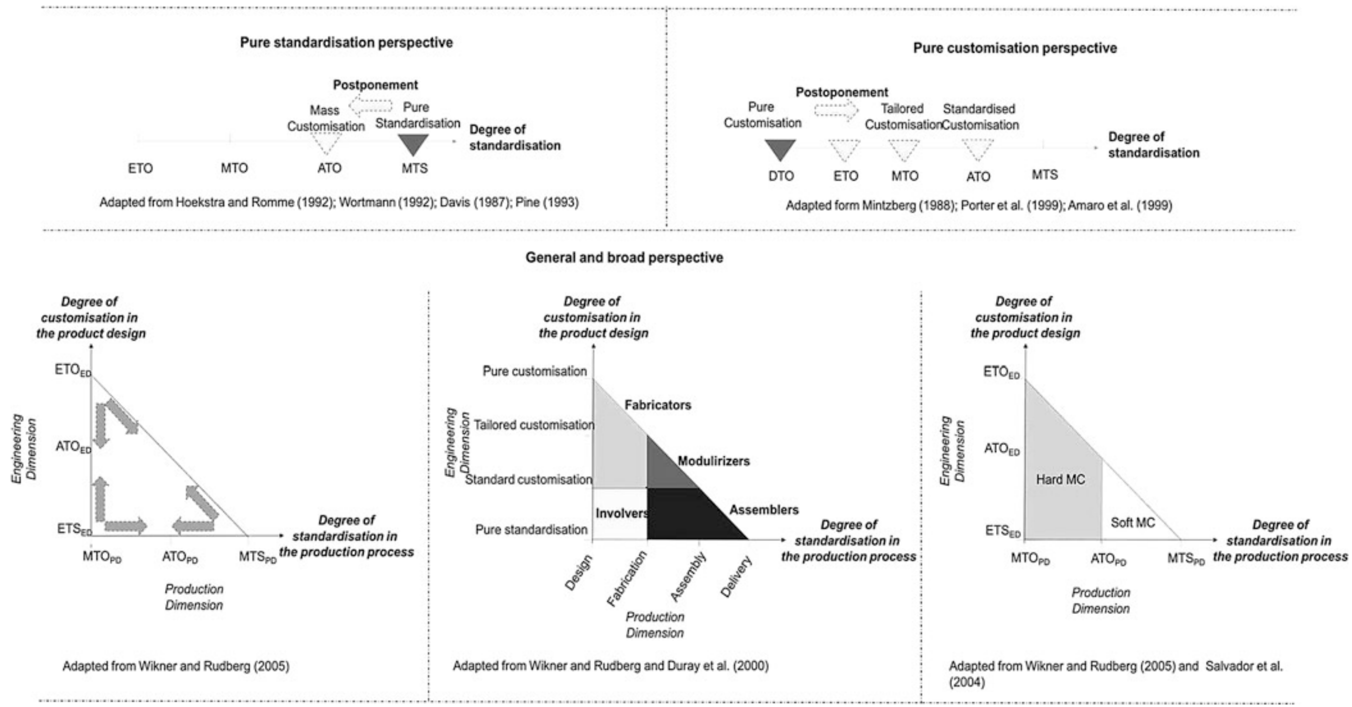

Fig. 5 The mass customisation, postponement and customer order decoupling point concepts from three different perspectives: pure standardisation, pure customisation, general and broad

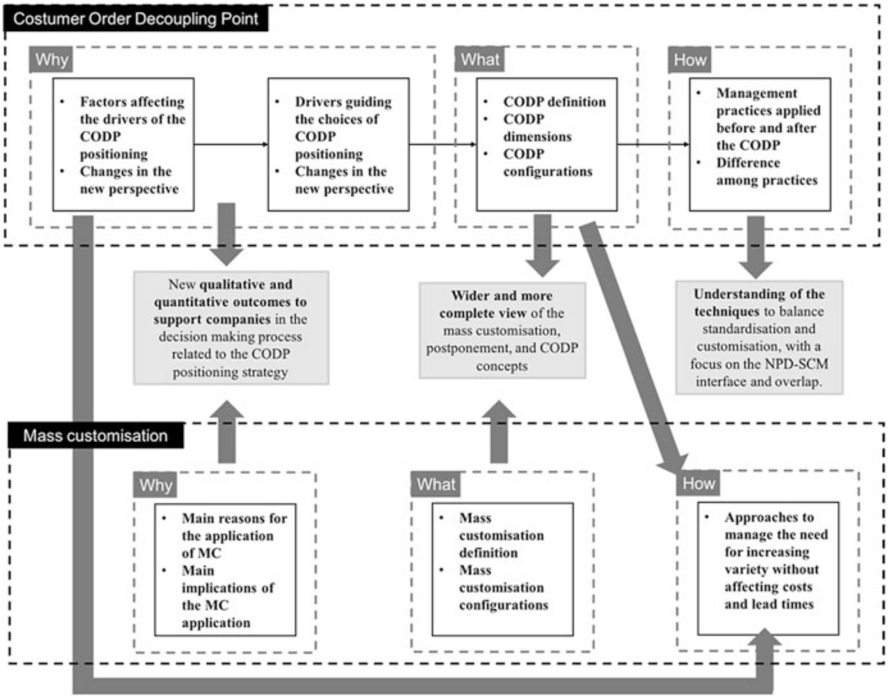

Fig. 6 Main framework developed from the literature

supply chain. Nevertheless, the CODP definition generated also disagreements in the literature over years when related to the ETO sector. The main divergence is related to the definition of what are the possible flows of activities to consider when the product design and development is strongly related to the supply chain management process. This includes the possibility to add dimensions to the CODP concept, looking at multiple flows of activities related to core business processes in the ETO context (i.e. sales, engineering, procurement, production), that are strongly correlated with each other. These flows are often managed concurrently and dynamically by ETO companies [52], with the aim to satisfy a specific customer order. Therefore, the "what" dimension opens a set of possible further research related to the conceptualisation of the CODP that should be addressed, such as:

- Is the CODP physical (stock material point), non-physical (information and/or product specification point) or both?
- How many flows of activities exist in which the CODP can be positioned? Are the activities included in a one-dimensional, two-dimensional or multi-dimensional flow?
- How many meaningful CODP configurations exist in each possible flow?

These research questions need to be investigated principally by empirically testing the different hypotheses present in the literature. A clear and complete definition of the CODP and its configurations, which incorporate perspectives from various industrial sectors, could help to understand the possible levels of customisation existing and the consequent different MC configurations achievable from both high customised and high standardised contexts. In this sense, it could be also interesting to better understand the interconnections among the CODP, MC and postponement concepts both from a theoretical and practical point of view. These interconnections are defined in different ways, from different perspectives and for different aims in the literature, making them not completely straightforward. The effort of classifying and organising the different viewpoints and testing them in real-life contexts could highlight the main gaps and needs in this field and encourage future research to apply a wider and more inclusive viewpoint when analysing these concepts. This answers partially also to RQ4, showing that one of the interconnections among the CODP and MC topics is given by their definitions and configurations including the ED to make the general concept more complete.

Moreover, the possibility to change the traditional view of the CODP unlocks further research also related to the other research questions. Indeed, as underlined in the literature review, the answer to the questions RQ2 *How does a company manage the activities upstream to and downstream from the CODP*? and RQ3 *Why does a company should shift the CODP backward or forward*? are strongly investigated in the material, one-dimensional CODP. But what happens if the CODP is non-material and requires more configurations and/or dimensions?

Thus, here interesting new questions are provided. About the how dimension:

- What are the management practices applied before and after this new CODP conceptualisation?
- Do the practices still difference before and after the CODP in a new CODP conceptualisation?

The techniques studied in the literature to manage standardised and customised activities are several, but often not interrelated one with the other. This correlation is important to make possible the understanding of the actual supply chain configurations that characterise the global and modern markets: where the standardisation and customisation must be necessary balanced. The traditional techniques should be studied in their application before and after the CODP, to understand how to reduce or, when possible, to eliminate the trade-off among productivity and flexibility, to obtain a global optimisation (i.e. to stay competitive by satisfying the market requirements with the desired products while reaching good performance in the internal processes needed to realise them). Especially, the techniques that allow the product development and supply chain management processes to be accomplished in combination and overlapping need to be more studied and stressed in the following studies related to the topic.

About the "why" dimension:

- What are the drivers guiding the choice of the new CODP positioning? Is still the P:D ratio the only driver for the positioning?

- What are the factors affecting the drivers guiding the choice of the new CODP positioning? Are still only market, product and production related?

Further research is needed to understand the companies' behaviour and the best practices to guide the decision-making process in different industrial sectors and customisation levels. This should be done by empirically analysing different industrial contexts, with a focus on the high customised ones, less analysed in the past works. This effort could help both academics and practitioners. On the one hand, the definition of new drivers and factors affecting the CODP positioning from a larger perspective could support new quantitative studies, which well addressed this subject, to measure the effects of different positioning on the product development and supply chain performance and to optimise the CODP location based on different drivers and factors identified. On the other hand, the outcome of qualitative and quantitative studies could support practitioners in choosing the best strategy to apply in a continuum of different possibilities, based on the characteristics of the context where they operate.

Finally, the why and how dimensions of the MC analysed in the previous chapter complete the answer to the last research question (RQ4). The why dimension, i.e. the MC reasons and implications, enriches the new qualitative and quantitative outcomes to support the CODP positioning, while the how perspective of MC, i.e. the strategies to implement MC, can be better defined, thanks to the in-depth analysis of the what and why perspective in the CODP framework. Therefore, further analysis in the MC theory and practice, including the 2D-CODP view, can support the study and application of MC in a broader perspective, in different industrial realities, from different starting points.

In conclusion, the contribution of the academic world in this field is highly required and essential to influence and guide all the industrial realities, and their entire supply chains, to stay competitive in the actual global markets. The main scope is to support them in (i) finding the most suitable configuration to balance the benefits of customisation with the ones provided by standardisation, (ii) managing the customised and standardised activities by acting on the engineering and production interfaces and (iii) achieving, according to the internal and external characteristics affecting their contexts, the most suitable 2D-CODP configuration and MC strategy to improve global performance.

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Mass Customization in Food Industries: Case and Literature Study

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Abstract The food industry currently faces demands for more diverse products. This introduces a different competitive environment than the food industry has traditionally experienced. A possible solution to the change in customer demand is to apply the business strategy, mass customization, which enables customized products at prices near that of mass-produced products. Although mass customization has been utilized in several different industries, the food industry has not yet seen this business strategy widely adopted. This paper presents a literature review, which only reveals few works within mass customization in the food industry. The limited literature covers food manufacturing processes, product configuration, and supply chain. To examine the potentials and challenges of mass customization in the food industry, a case study of a food manufacturer is conducted. It becomes evident that the case company has challenges with mastering the capabilities required to achieve mass customization. The challenges identified in this study are (1) no product solution space development, (2) limited knowledge of raw material, (3) manual equipment adjustment, (4) dedicated software and hardware solutions, and (5) limited choice navigation. In light of the listed challenges and the limited literature in the field, it is clear that more research is imperative in order to enable mass customization in the food industry.

Keywords Mass customization · Food industry · Case study · Literature study

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1 Introduction

Today, manufacturing companies face challenges that have followed globalization, e.g., the diversity and change of customer demands, increased need for customized products, fast-developing technologies, and focus on environmental sustainability [1, 2]. Manufacturing companies in the product ranges of durable and capital goods must respond to these challenges and efficiently produce a wider product range that fits different customer needs and continuously include new product technologies [3]. In order to remain competitive, mass customization is a widely adopted production strategy used to respond to the challenges of today, since individually configured products can be delivered at a cost near that of mass production [4, 5]. Mass customization is achieved mostly through modularized product/service design, flexible processes, and integration between supply chain members [6]. The term mass customization was first introduced in the late 1980s, defined by Pine [7] as "developing, producing, marketing and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want" [4]. The goal as a mass customizer is not to reach some idealized state, in which every customer wish is fulfilled at mass production costs. Rather, mass customization is the transition toward this unattainable state with focus on knowledge and development [5]. Salvador et al. [5] argue that one single best way to achieve mass customization does not exist. The managers of the company are required to tailor the approach in respect to the specific business. Nevertheless, Salvador et al. [5] identified the three fundamental capabilities to achieve mass customization (listed in Table 1).

Successful applications of mass customization have been reported a number of times in literature [6]. The general industry, especially durable goods and capital goods, has widely adopted mass customization extensively (e.g., cars, computers, etc.). Despite facing many of the same challenges in terms of increased variety and personalization, the chemical, pharmaceutical, and food industries have seen few examples of mass customization [8]. The food companies that have successfully applied mass customization operate within the scope of mixing or using simple processes [8]. This includes examples such as custom-mixed muesli and food products with custom print. Through a search in the Web of Science database, "mass customization" returns 2750 contributions, whereas "mass customization" AND "food" only return 31. This illustrates the limited published work in mass customization in the food industry.

Table 1 The three fundamental capabilities identified by Salvador et al. [5]

Solution space development	Robust process design	Choice navigation
"Identify the product attributes along which customer needs diverge" [5]	"Reuse or recombine existing organizational and value-chain resources to fulfill a stream of differentiated customers needs" [5]	"Support customers in identifying their own solutions while minimizing complexity and the burden of choice" [5]

The market change emphasizes the need for customized products, and the initial search for the published work indicates a requirement for additional studies within mass customization in the food industry. This leads to the following research question for this paper:

- What are the main potentials and challenges in adopting mass customization in the food industry?

2 Research Method

With the purpose of answering the research question, the method of this paper is divided in two stages. The paper first presents a review of the published work in the research area, followed by a case study. By diving into the literature, it becomes evident that a scarce number of papers and books address the topic of food industry in the context of mass customization. When this research was done, a search in early June 2017 for academic papers in the Web of Science database was conducted. The applied search consisted of a search in title, abstract, and keywords with the three phrases: "mass customization," "mass customization," and "food." The search included publications within articles, proceedings papers, and reviews, which were published after 2000. This search yielded 28 unique hits, and after a preliminary exploration of the abstracts, 20 papers remained. The preliminary exploration consists of an initial screening of the contributions within the topic of mass customization in food industry. The 20 papers were through an iterative process categorized into 3 areas: manufacturing processes, product configuration, and supply chain. This categorization is based on preliminary exploration of the abstracts in order to frame the subject of mass customization in food industry. Keywords for the papers in each category are illustrated in Table 2.

A case study is presented in this paper in order to clarify the potentials and challenges of adopting mass customization in a food manufacturing company. The company is searching for ways to accommodate the new market trends, in which the customers demand variation in the products, but still at low prices. The case study was conducted as a combination of identifying challenges through data collection, observation, and interviews. Moreover, the case study was performed over a span of 4 months, including regular interviews with various stakeholders and visits to the production lines. This paper explores how the case company responds to the three fundamental capabilities listed by Salvador et al. [5] in Table 1.

Table 2 Keywords on the literature study within the three main subjects

Food manufacturing processes	Product configuration	Supply chain
3D print	Configurators	Food chain
Late customization	Sustainability	Supply chain
Flexibility requirement	Consumer agriculture	Software
Robot in SME	Personalizing nutrition	
Software		

3 Literature Study

3.1 Food Manufacturing Processes

Food manufacturing companies have mainly operated with fixed production lines, in which it is costly to make adjustments in the plant layout to change functionality and thereby accommodate new product variants [9]. However, it is preferable to have a system, which is quick to design, control, and reconfigure, in order to accommodate new requests in the market [9]. McIntosh et al. [8] state that there is significant potential in implementing mass customization in the food industry; however, due to product and process characteristics, doing so requires alternative development approaches. The differences in product characteristics and process characteristics include [8]:

1. Customization by mixing rather than mechanical assembly
2. Product and material decay
3. Cleaning requirements between producing different products
4. Difficulties in performing modular product design
5. Distribution requirements

Although it is far from common practice, the food industry is beginning to see companies utilizing mass customization as their business strategy [10]. To accommodate the characteristics listed by McIntosh et al. [8], different initiatives are reported in the literature. Fisher et al. [11] address the issue of food customization from a production system design perspective, in which constraint modeling is applied to design a production system with late customization and increased responsiveness. Sorouri et al. [9] study intelligent products and machine controllers that can cooperate with one another without human intervention, and the outcome is a laboratory production system that offers customized ice cream.

In the context of food manufacturing processes, another solution for addressing the demand of mass customization is 3D printing of food. From the 20 papers in this study, 4 were in the field of 3D printing of food. The 3D printing of food is a new kind of food process that utilizes food materials in an additive manufacturing process [12, 13]. The process has potential to embed customized textures, colors, and flavors within solid and gelled foods [12]. Wegrzyn et al. [12] denote that one of the facilitators, in the process of the 3D printing of food, is highly standardized materials. This can create potential challenges because physical measurements made in the food industry have been derived empirically rather than relating to the fundamental physical properties of foods [14]. In addition to focusing on empirical measurements, Aguilera et al. [14] describe that unlike other manufacturing industries, the measurement of food qualities, including appearance, texture, and flavor, is performed subjectively against a set of criteria established by customer experience. The 3D printing of food can also be used for personalizing nutrition. Thus, Lipton [15] argues that 3D printing is an ideal family of technologies for reaching a food product that is personalized to each person's health context.

A limited amount of work is performed in the field of mass customization in the food industry in relation to food manufacturing processes. The work performed is limited to examples on a conceptual level, and more work is needed to enable the food industry to adopt or adjust the manufacturing process and thereby achieve mass customization.

3.2 Product Configuration

The consumers' awareness of what they eat and how the food affects the health is on a high and still rising [16]. Thus, there is increased focus on individual food composition [14]. This enables customers with different health conditions, e.g., high or low blood pressure, diabetes, or other specific needs, to have better choices in food in relation to their physique. Boland [16] denotes that customization in the fast food industry is common practice for such items as pizzas, deli sandwiches, and hamburgers. Here components such as grated or sliced cheese, meat, and vegetables are assembled according to the customer's preferences. Furthermore, in the aspect of product personalization, a study by Kolb et al. [10] identifies 88 food product configurators. Thirty-six of these configurators customize both the ingredients and packaging, 30 customize purely ingredients, and 22 customize only packaging. Studying the list of companies that provide these configurators, it becomes evident that many of these do not work in the mass production paradigm but represent craft production.

Apart from the fast food industry and low-volume craft production, the food manufacturing industry offers mostly products developed with limited involvement of the customer. Nevertheless, some mass-producing companies are moving toward successful integration of mass customization, e.g., Weight Watchers and Jenny Craig [16]. These companies offer premade calorie-controlled meals intended for customers that need to manage their body weight.

In summation, the need for personalizing food products is on the rise, and one solution for accommodating this need is mass customization. The fast food industries have been successful with involving the customer for many years, and this strategy is moving into the food industry.

3.3 Supply Chain

To accommodate the changes in market demand, the business strategy, mass customization, can be utilized (see Sect. 1). To enable mass customization, the literature study revealed a common denominator in the need for modification of the current supply chain setup. Mertins et al. [17] have investigated customization of information in food supply chains to increase interoperability in food production networks. This research does not address customization of the product itself but provides mechanisms, which enable increased product variety in a supply chain context, thus supporting mass customization. Similarly, Trienekens et al. [18] investigate how transparency in food supply chains enables variable consumer demands, also supporting mass customization. The findings of Trienekens et al. [18] consist of a framework for transparency analysis in food supply chains and information technology applications needed to apply this. Verdouw et al. [19] argue that business processes in the agriculture, food, and logistics sectors still rely heavily on human input to the IT systems. This results in delays between the occurrence of an event in the real world and the registration of it in the IT systems, which causes a limited end-to-end visibility of the business networks [19]. Therefore, when moving from mass production toward mass customization, a mass-customizable software is needed to support dynamics in the agriculture, food, and logistics sectors [19].

Awareness of having a supply chain strategy and more transparency between the different businesses are increasing in the food and agriculture industry. However, the literature study did not reveal businesses with a mature solution to accommodating mass customization in their supply chain. One of the facilitators is a software that can provide more end-to-end visibility of the supply chain, as well as the entire business network.

3.4 Findings

Evaluating on the literature presented in Sects. 3.1, 3.2, and 3.3, it becomes indisputable that the subject of mass customization in the food industry is not thoroughly exhausted. The examples listed in the literature are primarily on a conceptual level. Moreover, the existing literature focuses very little on documenting the challenges of adopting mass customization and provides no guidelines for successfully implementing it. This emphasizes the need for further research in the food sector that will enable the industry to accommodate the changes in market demand.

4 Case Study

Additional research in the field of mass customization in the food industry is essential. Consequently, a case study is conducted to illuminate on the challenges in the food industry. The case company of this research manufactures frozen and fresh bakery products, and its primary market is in B2B. It is a large international bakery group with bakeries around the world and approximately 6000 employees. A large range of different bakery products are produced; however manufacturing sites are dedicated to a limited product range, such as pastry, daily fresh, and/or frozen products. The company is searching for ways to accommodate the new market trends in which customers demand variation in products but still at low prices.

This study documents the current state of the case company in terms of how far the company is from realizing the three capabilities necessary to achieve mass customization, identified by Salvador et al. [5], and listed in Table 1. Furthermore, challenges in realizing these capabilities and suggestions on the next step of how the company may accomplish this are presented. The challenges denoted in this paper take mainly offset in one of the bakery plants.

4.1 Solution Space Development

In the case company, new products are typically developed on the basis of the existing products. The product development is unsystematic and based on the individual employee's knowledge and know-how/craftsmanship. In the current product portfolio at the case company, there is a great deviation in planned production time of the different products. For instance, one product is produced for approximately 400 h and another for 4 h, during a span of 5 months. This is the effect of the market demand for each individual product. Moreover, it raises the question: Are the customers interested in the variety offered by the company? There is no direct feedback loop of the customer preferences to the company solution space. Furthermore, the future solution space is not accommodated in the present setup at the case company.

An increase in product variety will lead to new products that differ in size, shape, topping, filling, taste, and labeling. Moreover, a systematic approach toward the development of the product solution space is lacking. The range of the parameters for new products is not available throughout the value chain. Consequently, there exist no clear guidelines for the product developer of what the manufacturing setup facilitates. Moreover, a production platform does not exist, and thus the case company does not combine a production platform with the product portfolio.

Challenges in Solution Space Development

The literature study in this paper does not reveal literature that addresses solution space development in relation to mass customization in the food industry. Nevertheless, to accommodate mass customization, according to Salvador et al. [5], the case company needs to have a strategy for solution space development. There is an assumption at the case company that by challenging the current solution space, a wider range of customers can be reached and thereby increase profits. The next step is, thus, to develop a systematic approach for establishing the product portfolio at the case company with respect to the future customer demand.

As the solution space is closely interconnected with what the manufacturing setup facilitates, this calls for interaction between the product paradigm and the manufacturing paradigm.

4.2 Robust Process Design

In bread production, the flour quality has an implicit effect on the final bread product. The case company determines the range of flour quality, though in-depth knowledge of how the different flour properties correlate with the final product is missing. The properties of the different batches, which affect the production processes, are therefore not logged or used to control the bread production. Moreover, the amount of baking improvers—such as enzymes and surfactants—is likewise determined empirically, and it is not always well understood how they affect each other. In summary, the case company has incomplete knowledge about the properties of the ingredients and the effect of them on the final product. Consequently, no guidelines or standards exist in the development of new products.

The settings for the machine parameters for each product are determined empirically. The case company does not have a digitalized setup; instead the production is controlled by a human operator of the manufacturing setup. Trained employees continuously adjust the production processes when it is affected by variation in the temperature in the production area or variation in flour properties between different batches of flour. However, the knowledge of how to adjust the equipment is largely tacit, and it is thus difficult to utilize this knowledge toward making a more flexible and robust production. Apart from a few sensors, the properties of the dough—like elasticity and resistance to deformation—are not measured. The few sensors that do exist as part of the production setup are only used to control one part of the machine. Thereby, every production cell operates individually, and there is no digitalized interconnection between the cells. This results in manufacturing setups that are difficult and costly to reconfigure when introducing new products. The missing motivation in the case company to log the production data and use automatized adjustments of the equipment might be justified by the limited understanding of the effect from changes in the production parameters. When parts of the production setup are updated or new parts are acquired, it is not done with respect to the next generation of products. The software and hardware solutions are purchased with the intention of solving the existing problems. This results in dedicated manufacturing setups with low flexibility toward introducing new products.

Challenges in Robust Process Design

In order for the case company to utilize mass customization, the production process must be robust. Nevertheless, the case company has challenges with obtaining and managing a robust process design. The challenges are limited knowledge of the raw materials, manual equipment adjustment, and dedicated software and hardware solutions. These challenges result in a manufacturing process, which is difficult for the company to control. The ramp-up time is not measured in the existing setup, but the company assumes the ramp-up time at average represents 20% of the total production time for each production batch. The changeover time is approximately 5–30% of the production time, depending on whether the new product is in the same product family as the previous one. It is thus not feasible to adopt mass customization due to the combination of long ramp-up time and changeover time.

The case company is missing knowledge of correlations between the properties of the ingredients, the synergetic effects, the production processes, and the effects on the final product. The literature reveals that some correlations between properties of ingredients and the final product can be found, e.g. between the amount of gluten in the flour and the final bread volume [20, 21]. However, these correlations are also affected by changes in recipe and production process [22]. For example, the ratio between water and flour influences the mixing time, which again influences other properties like the extensibility of the dough [21]. The case company, therefore, needs to identify the important properties of the ingredients and to determine how these are correlated specifically with their products. The literature presents different parameters that may be important, but this has to be tested for the specific production at the case company. This insight will reduce the time to market for new products and introduce more flexibility in the product development phase. Additionally, more knowledge about how the dough is behaving during the processing and how the processing affects the final product can also be used to adjust the production process continually. Today the adjustments of the production processes are based on the experience of the employees. More quantifiable knowledge about how the production processes should be adjusted can reduce the waste and the changeover time.

4.3 Choice Navigation

The current practice is that a new customer has a conversation with sales and marketing before purchasing the goods. Before the meeting between customer and the company, some preselection is performed by the company based on national preferences. Nevertheless, no standardized procedure exists, and the preselection is based on the experience of the individual employee in accordance with the expected customer preferences.

The customer can choose products from a catalog. If a customer requests a product that is not part of the product portfolio, it might still be possible to purchase. However, the time to market is unknown. One of the reasons for this uncertainty is the undefined product solution space and undefined manufacturing solution space.

Challenges in Choice Navigation

Only a very simple catalog-based choice navigation exists at the case company. The customer preferences are not logged and thereby not used for optimizing the selection process. The case company can benefit from a solution in which choice navigation is not merely based on employee know-how. One solution is assortment matching, a software that automatically demonstrates a solution for the customers by matching needs with attributes of the existing solution space [5]. Furthermore, exploring the potential for the case company to utilize a configurator to create visual representations of the variations in products can be beneficial.

5 Conclusion

This paper covers the limited literature in the field of mass customization in the food industry. The current literature is categorized and accompanied by a clarification of the new research and does not reveal a thoroughly exhausted subject of mass customization in food industry. Moreover, the case study reveals challenges within the three capabilities to achieve mass customization listed by Salvador et al. [5]. The main challenges founded in the case study are as follows:

- No product solution space development
- Limited knowledge of raw materials
- Manual equipment adjustment
- Dedicated software and hardware solutions
- Limited choice navigation

Even though this research is conceptual, based on literature review and a single case, it is evident that further research is essential in order to address challenges in implementing mass customization in the food industry, as well as identifying operational tools useful for enabling mass customization in the food industry.

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Can the SME Successfully Adopt Mass Customization?

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Abstract The mass customization (MC) literature has, so far, primarily focused on how large enterprises (LEs) successfully can achieve mass customization, neglecting the small- and medium-sized enterprise (SME). Since SMEs constitute a major part of the global economy, this paper has the purpose to examine whether the MC literature's propositions and best practices are directly transferable to SMEs. Based on data from a large international survey, the paper concludes that, from an environmental perspective, both LEs and SMEs could use MC to cope with fluctuations and attain a competitive edge. The results also indicate that LEs have implemented all but one of the studied MC-enabling practices to a much higher degree than SMEs. To become successful mass customizers, the average SME still has to improve substantially. More specifically, the results indicate that the average SME needs to (a) increase the degree of communication and collaboration with customers and suppliers; (b) integrate design and manufacturing organizationally and through manufacturing and design technology, tools, and techniques; (c) control and improve the quality and flexibility of its manufacturing processes, machinery, and equipment; and (d) create an organization supporting open communication, employee autonomy, and continuous improvement.

Keywords Small- and medium-sized enterprises · Mass customization · Survey research

1 Introduction

In his prominent book about mass customization, Joseph Pine [1] describes how changes in the competitive landscape in the 1990s created the need for manufacturers to move from mass production to mass customization, where "variety

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and customization supplant standardized products, heterogeneous and fragmented markets spring from homogenous markets, and product life cycles and development cycles spiral downward" [p. 34]. In other words, he described how the marketplace had changed to one where customers no longer are satisfied with the choice between either low-cost standardized goods or high-cost personalized products, but require a combination of the two. In order to enable firms in "developing, producing, marketing and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want" [1, p. 44], Pine suggested that the best way of supporting the low-cost production of individually customized products and services was through the adoption of modularization. Since then, an Abundance of literature has elaborated on the mechanisms whereby firms can achieve successful MC (see Table 1 for popular examples).

Many of the MC authors produce theory directed at or based on evidence from larger enterprises (see, for instance, [1–4]). Yet, not all firms that aim to combine flexibility with productivity can be classified as being a LE. In particular, there is one group of firms often neglected in the MC literature – the small- and medium-sized enterprises attempting to compete in this new competitive environment. This is despite of the fact that SMEs play a major role in the global economy. In the EU, SMEs account for over 99% of the total number of enterprises and around two-thirds of the employment, as well as contribute 57% of the value added [5]. In the Asia Pacific region, the numbers only are slightly smaller; SMEs account for over 97% of the total number of enterprises and over half of the employment and contribute with between 20% and 50% of the GDP in the majority of the economies [6].

In other fields of literature, researchers have started to recognize that SMEs often require different approaches than their larger counterparts, including researchers in the field of knowledge management (e.g., [10]), planning and control (e.g., [11]), performance measurement (e.g., [12]), innovation research (e.g., [13, 14]), and environmental management (e.g., [15, 16]). As noted by Taps et al. [17], there is, however, little MC literature that focuses specifically on SMEs. To further this research agenda, this paper has the overall purpose to examine whether SMEs and LEs differ from an MC perspective.

The emergence of the MC paradigm was partially a reaction to the contextual changes manufacturers experienced during the 1990s [1]. In particular, market fragmentation, shortened product life cycles, increased levels of demand uncertainty, and a higher intensity of technological change made it necessary for mass manufacturers to shift their focus from the mass production of high-volume standardized products to using these mass production techniques to deliver products tailored to the demand of the individual customer [1, 4, 23]. The question is, however, whether these environmental changes are specific to the large, mass manufacturer only or whether they also are experienced by the SME.

In addition to changes in the environment, the emergence of MC can also be attributed to technological changes that made it feasible for the manufacturer to both achieve cost-efficient production *and* provide product variety and flexibility [23]. These technological changes have improved, among others, the ease to which firms can communicate and coordinate internally across functions and externally

Table 1 Four articles proposing enablers of successful MC

[3]	*MC building blocks*
Modular product design	A product should be designed so that it consists of independent modules that can be assembled into different forms of the product easily and independently
Modular process design	Manufacturing processes should be designed so that they consist of independent modules that can be moved and rearranged easily to support different distribution network designs
Agile supply networks	The supply network should be able to supply the basic product to the facilities forming the customization in a cost-effective manner and must have the flexibility and responsiveness to take individual customers' orders and deliver the finished, customized goods quickly
[4]	*MC components*
Elicitation	System choice boards, design technologies (virtual reality and multimedia technology), and sales force training
Process flexibility	Modular product combined with postponement of product differentiation and flexible manufacturing systems (maximize setup commonality, automated handling systems, industrial robots, CAD/CAM, tooling)
Logistics	Coordinated supply chain (virtual integration, JIT inventory) and integrated logistics information system (bar codes and scanning)
[8]	*MC capabilities*
Solution space development	Identify the product attributes along which customer needs diverge (through, e.g., innovation tool kits, virtual concept testing, customer experience intelligence)
Robust process design	Reuse or recombine existing organizational and value chain resources to fulfill a stream of differentiating needs (through, e.g., flexible automation, process modularity, and adaptive human capital)
Choice navigation	Support customers in identifying their own solution while minimizing the complexity and burden of choice (through, e.g., assortment matching, fast-cycle trial-and-error learning, embedded configuration)
[9]	*MC enablers*
Processes and methodologies	Agile manufacturing, supply chain management, customer-driven design and manufacture, and lean manufacturing
Technologies	Advanced and flexible manufacturing systems
Customer information transfer	Through having a catalogue of options, collecting and storing information on customer choices, translating customer choices into product design features, and manufacturing instructions

with suppliers and customers. Increased internal and external coordination has provided the firm with the ability to more easily obtain information on consumer preferences and effectively translate these into products that adhere to the technical product constraints and the process capabilities of the firm and its supply chain [7]. Further, these information technologies allow the firm to efficiently plan, control, and manage the complexity inherent to the manufacturing of mass-customized products. MC also has been made possible through the emergence of advanced manufacturing technologies, which enable mass customizers to design manufacturing systems flexible enough to efficiently deal with demand fluctuations and the continual introduction of new product variants. A great deal of other technologies, techniques, and practices play a role in successful MC, including work design principles, product development techniques, time-based manufacturing practices, quality management practices, and so forth. However, many of these technologies and techniques require either substantial financial investments or a high degree of know-how. As SMEs have a more limited amount of financial, time, and human resources, it begs the question whether and how smaller firms can adopt these MC enablers.

In light of this, this paper's overall aim is twofold and seeks to investigate (1) whether differences between the SME and LE environmental context influence the appropriateness of mass customization for SMEs and (2) whether SMEs and LEs differ in the extent to which they have adopted MC-related practices. In order to provide generalizable evidence about the differences between LEs and SMEs, this paper employs data collected via the International Manufacturing Strategy Survey conducted in 2013. Before presenting the results of this survey, Sect. 3 will define SMEs and outline key differences between SMEs and LEs, and Sect. 4 will present the research design and general sample characteristics.

2 SME Definition and Characteristics

The definition of what an SME actually constitutes varies; however, a commonly adopted definition of the SME is provided by the European Union, which uses the number of employees and the firm's turnover and balance sheet results to distinguish between micro, small-, medium-sized and large enterprises (Table 2). Here, SMEs are defined as having between 10 and 249 employees, a turnover between €2 million and €50 million or a balance sheet total between €2 million and €43 million [18].

Table 2 EU SME definition

Category	Staff headcount	Turnover	Balance sheet
Micro	< 10	≤ €2 million	≤ €2 million
Small	10–49	≤ €10 million	≤ €10 million
Medium	50–250	≤ €50 million	≤ €43 million
Large	> 250	> €50 million	> €43 million

However, it is not firm size or financial characteristics that lead us to suggest that SMEs likely need a different approach to MC than their larger counterparts, but rather other key differences between these two groups of firms. SMEs traditionally have a smaller amount of time, financial, and human resources compared to LEs [10], and on top of that, SMEs are likely to have a narrower span of activity, be sited in one single location, as well as target fewer market segments and a smaller amount of customers [12, 19]. Others also note that the two groups of firms differ in terms of their strategical and cultural behavior and organizational structure. In particular, smaller firms often exhibit more unplanned, reactive behavior and pursue informal, organic dynamic strategies [19, 20]. Further, they often have flatter and, therefore, more flexible structures compared to larger companies, display lower degrees of standardization and formalization, and are managed via personal, centralized control where company decisions and behavior are highly dictated by the central owners' or managers' personal outlook [12, 19].

Given these fundamental differences between SMEs and their larger counterparts, this paper suggests that SMEs obtain successful MC in a different manner than LEs do. Many of the technologies suggested to support firms in their endeavor to adopt mass customization require substantial financial investments, too vast for the average SME. This includes the purchase of new manufacturing technology such as advanced manufacturing systems, investing in new design technology such as virtual reality and multimedia technology, implementing integrated information systems, and so forth. As noted by Svensson and Barfod [21], for most SMEs, becoming mass customizers is not a matter of purchasing new machines or implementing automation or other technology, but starts off with identifying and generating the information needed for making decisions that support a more efficient production. Larger manufacturers can be expected to have the level of standardization and volume to achieve the "mass" in mass customization. Their struggle with mass customization will be to adopt a more customer-responsive operational setup and change their limited product portfolio to a more diverse one, capable of addressing a larger variety of customer needs. SMEs, on the other hand, might face another struggle. Being less formalized and standardized than large enterprises, and producing in smaller volumes, the first step for SMEs in their effort to become mass customizers might be to standardize or ensure a greater reuse of the internal and external resources needed to create the requisite variety. In other words, an appropriate initial focus for SMEs pursuing MC could be to manage the negative impact of product variety on internal operating performance and thereby achieve higher levels of cost-efficiency [22].

Some of the techniques and approaches to MC that are less investment-heavy require instead competences and know-how that might not reside within the SME. These knowledge-intensive approaches include the design of standardized, customizable products and modular processes, the adoption of agile and/or lean manufacturing, and the creation of a more coordinated supply chain. Further, given their relatively narrow span of activity, SMEs might be more dependent on external players when pursuing MC. For instance, it could require them to collaborate with suppliers during design and development in an effort to ensure that the supplier's products can function in multiple of the SMEs' final product offerings.

3 Research Design

The paper employs data collected in 2013 during the sixth International Manufacturing Strategy Survey (IMSS), a survey that explores the development and performance effects of manufacturing strategies in single manufacturing and/or assembly plants. The target respondent for the survey is the operations, manufacturing, or technical manager of these plants. Data collection was conducted in 22 countries, where a total of 837 valid responses were collected from the 2586 participants who originally agreed to participate, resulting in a final response rate of 32%.

Two criteria were used to determine whether the given firm in the sample was an SME, LE, or other type of firm, that is, the number of employees in the firm and the firm's turnover. To recall, the EU criteria for an SME is that it has to have between 10 and 249 employees and a turnover equal or below €50 million. However, after analyzing the data collected through the IMSS, it became evident that 72% of the firms with an employee count that lived up to the criteria had a total turnover larger than €50 million. Therefore, it was chosen to broaden the definition of SMEs to include firms with revenues below €50 million, but with up to 499 employees as well as firms with revenues between €50 million and €100 million and up to 249 employees (see Table 3). A total of 625 responses were used for the statistical tests conducted in this paper, 273 firms categorized as SMEs and 353 firms categorized as LEs.

Tables 4, 5, 6, and 7 elaborate on the sample characteristics. Tables 4, 5, and 6 show, respectively, the types of geographical regions, industries, and networks addressed in the total sample and subsamples. Compared to the distribution in the total sample, relatively more SME responses were from Eastern Europe, whereas a relatively high amount of LE responses were Asian. There are also differences in the type of industries SMEs and LEs typically are part of; i.e., a higher portion of SME's manufacture fabricated metal products, whereas LEs produce motor vehicles, trailers, and semitrailers to a larger degree. The network characteristics of

Table 3 SME, large and other enterprises in the sample

	Revenue (million Euros)				
	<10	10-50	50-100	100-500	>500
0 – 9	0	0	1	1	0
10 – 49	2	4	9	4	2
50 – 249	20	74	139	83	26
250 – 499	3	22	49	31	14
500 – 4999	9	34	87	67	26
> 5000	2	11	37	30	11

SMEs   Large Enterprises

Table 4 Geographical distribution

Region	Countries	Total		SME		LE	
		N	%	N	%	N	%
Americas	BRA, CAN, USA	106	*13*	33	*12*	53	*15*
Asia	CHN, JPN, MYS, TWN	252	*30*	56	*21*	126	*36*
Northern Europe	DNK, FIN, NOR, SWE	131	*16*	48	*18*	53	*15*
Western Europe	BEL, DEU, NLD, CHE	123	*15*	40	*15*	43	*12*
Southern Europe	ITA, PRT, ESP	111	*13*	37	*14*	43	*12*
Eastern Europe	HUN, ROU, SVN	114	*14*	59	*22*	43	*10*

Table 5 Type of industry

Type of industry	Total		SME		LE	
	N	%	N	%	N	%
ISIC 25: Fabricated metal products	271	*32*	109	*40*	93	*26*
ISIC 26: Computer, electronic, and optical products	96	*11*	24	*9*	48	*14*
ISIC 27: Electrical equipment	135	*16*	38	*14*	61	*17*
ISIC 28:Machinery and equipment n.e.c.	215	*26*	80	*29*	78	*22*
ISIC 29: Motor vehicles, trailers, and semitrailers	60	*7*	13	*5*	53	*15*
ISIC 30: Other transport equipment	40	*5*	9	*3*	19	*5*

Table 6 Type of network

Type of network	Total		SME		LE	
	N	%	N	%	N	%
Stand-alone: Only this plant belongs to the company	264	*32*	139	*51*	57	*17*
Domestic: All the plants are located in one country	133	*16*	42	*16*	59	*17*
Regional: All the plants are located in one continent	84	*10*	20	*7*	37	*11*
Global: Plants are located in different continents	341	*41*	69	*26*	191	*56*

the two groups of firms are also very different. The SME sample primarily consists of stand-alone plants (51%), but also has a quite high representation of firms with domestic networks (16%) and global networks (17%). The LE sample has firms primarily belonging to the latter group, firms with global networks (56%), but also includes stand-alone plants (17%) and plants with domestic networks (17%).

Table 7 compares the SME and LE samples in terms of the types of products sold, goods purchased, manufacturing process employed, and customer addressed by the two groups. There are no substantial differences between the types of products the two groups of firms sell or purchase, but SMEs do sell their products relatively more to end-users and less to manufacturers of finished products. SMEs also use a relatively higher percentage of one-of-a-kind production and relatively less mass production, as well as design their products to order to a higher degree when compared to larger enterprises.

Table 7 Product, manufacturing, purchase, and customer types

	SME	LE		SME	LE
Sales type (% of total sales)			*Purchase type* (% of total purchase)		
Parts and components	29%	33%	Raw materials	46%	46%
Assembled products	60%	58%	Parts/components	37%	39%
Services	11%	9%	Subassemblies/systems	18%	15%
Fabrication (% of total volume)			*Assembly* (% of total volume)		
One-of-a-kind production	38%	26%	One-of-a-kind production	46%	33%
Batch production	49%	50%	Batch production	44%	43%
Mass production	13%	24%	Mass production	10%	23%
Decoupling point (% of customer orders)			*Customer type* (% of sales)		
Design to order	22%	17%	Man. of subsystems	16%	18%
Manufacture to order	41%	42%	Man. of finished products	27%	35%
Assembly to order	22%	24%	Wholesalers	25%	25%
Manufacture to stock	15%	16%	End-users	32%	23%

4 Findings

This section compares SMEs and LEs in respect to the manner they perceive their environmental competitiveness and dynamics and the degree to which they have implemented action programs to achieve design, internal and external integration, as well as action programs related to organization, manufacturing, and quality. To analyze the differences, independent sample t-tests were conducted, where, for each test, the rating mean (M) of the SME and LE sample, the standard deviation of the mean (SD), the mean difference (ΔM) between the two groups, and the significance of the t-test are indicated.

4.1 Environment

The emergence of MC has often been attributed to changes in the environmental conditions the firm faces. In particular, researchers note that the popularity of MC is driven by the fragmentation of market segments into smaller niches, more uncertainty in demand, an increased pace of technological change, and shortened product cycles [1, 4, 23]. From that perspective, it is interesting to analyze whether these environmental conditions are specific to LEs only, or also are experienced by the SME. To study if and how the environmental context differs between SMEs and LEs, this paper uses items reflecting the degree to which the firm experiences dynamics and competition and items characterizing the firm's marketplace (in Table 8). The marketplace is analyzed through two items: the number of market segments the firm addresses (market span) and the number of competitors in the market (market concentration). To assess environmental competitiveness, the survey

Table 8 Environmental competitiveness

	SME		LE		
	M	SD	M	SD	ΔM
Rate of technological change (*very low–high*)	2.97	0.95	3.42	0.95	−0.46**
Market span (*few–many segments*)	3.24	0.98	3.52	1.00	−0.37**
Market concentration *(few–many competitors)*	3.37	1.10	3.49	1.10	−0.12
Competitive rivalry within industry (*very low–high*)	3.79	0.96	3.94	0.90	−0.15*
Market entry *(closed–open to new players)*	2.99	1.11	2.83	1.08	0.16
Threat for product substitution (*very low–high*)	2.94	1.08	2.99	1.10	−0.05
Bargaining power of suppliers (*very weak–strong*)	3.09	0.92	3.08	0.88	−0.01
Bargaining power of customers (*very weak–strong*)	3.61	1.01	3.73	0.91	−0.12

*Note: *p < 0.05; **p < 0.01 (applies to all remaining tables). Scale: How the firm perceives its environment from 1 to 5 (The parentheses indicate the specific extremes)*

Table 9 Environmental dynamics

	SME		LE		
	M	SD	M	SD	ΔM
Your demand fluctuates drastically from week to week	2.77	1.10	2.66	1.17	0.11
Your total manufacturing volume fluctuates drastically from week to week	2.54	0.99	2.45	1.07	0.09
The mix of products you produce changes considerably from week to week	2.82	1.14	2.80	1.18	0.02
Your supply requirements (volume and mix) vary drastically from week to week	2.76	1.01	2.63	1.11	0.14
Your products are characterized by a lot of technical modifications	2.72	1.15	2.71	1.18	0.01
Your suppliers frequently need to carry out modifications to the parts/components they deliver to your plant	2.19	1.02	2.34	1.12	−0.14

Scale: Degree to which the firm agrees with the statement from 1 (not at all) to 5 (to a great extent)

takes point of departure in the competitive forces proposed by Porter [24], i.e., competitive rivalry, market entry, product substitution, supplier bargaining power, and customer bargaining power. Environmental dynamics is assessed by an item reflecting the degree to which the firm experiences technological change and the items, in Table 9, that measure the type and degree of fluctuations the firm experiences.

The largest difference between the two groups is that LEs experience a significant higher degree of technological change compared to SMEs. This is interesting as it, especially in entrepreneurship literature, is presumed that SMEs need to have an innovative edge in order to be successful in competing against larger firms [13]. In turn, one should expect these entrepreneurial SMEs to experience a relatively high degree of technological change, or at least be the driver of these changes. The results of the IMSS, however, indicate that SMEs (also) exist in relatively stable environments, with fewer technological disruptions. When it comes to other types of dynamics, that is, the degree of fluctuations in the firms' own demand, manufacturing volume, product mix, supply requirements, as well as the degree to which the firm or its suppliers have to carry out modifications, the results indicate that there are no significant differences between the SMEs and LEs.

All in all, although SMEs do not experience the same rate of technological change, which is one of the drivers behind the popularization of mass customization, they do experience similar levels of competitiveness and fluctuations. So, from the perspective of the external environment, MC indeed seems as a valid strategy for both LEs and SMEs in order to attain a competitive edge and cope with fluctuations.

4.2 Design, Internal, and External Integration

To measure the differences between the degree to which SMEs and LEs have implemented design integration, the survey uses the items listed in Table 10. The items reflect three categories of integration mechanisms identified by Paashuis and Boer [25]: (1) integration by organization (organizational integration, informal mechanisms), (2) integration by process (process integration), and (3) integration by technology (technological integration, communication technologies, integrating tools and techniques, and design integration). Table 11 contains the items for internal integration with purchasing and sales as well as the items reflecting external integration with customers and suppliers. These items have been recently verified by Yang et al. [26].

The importance of integration in MC is best put into words by Da Silveira et al. [9], “An MC system is highly dependent on well-designed information systems that

Table 10 Design integration

	SME		LE		
	M	SD	M	SD	ΔM
Informal mechanisms (e.g., *direct, face-to-face communication, information discussion,* ad hoc *meetings*)	3.18	1.00	3.51	0.93	−0.33**
Design integration between product development and manufacturing (e.g., *platform design, modularization*)	2.99	1.05	3.36	0.96	−0.37**
Organizational integration between product development and manufacturing (e.g., *cross-functional teams*)	2.93	1.11	3.28	0.99	−0.34**
Technological integration between product development and manufacturing (e.g., *CAD, CAM, CAPP*)	2.74	1.19	3.22	1.10	−0.48**
Integrating tools and techniques (e.g., *failure mode and effect analysis, QFD, rapid prototyping*)	2.50	1.21	3.31	1.10	−0.80**
Communication technologies (e.g., *teleconferencing, web meeting, intranet, and social media*)	2.92	1.14	3.67	1.02	−0.74**
Forms of process standardization (e.g., *stage-gate process, design reviews, performance management*)	2.79	1.11	3.45	1.02	−0.66**

Scale: The current level of implementation from 1 (none) to 5 (high) ((applies to all remaining tables)

Table 11 Internal and external integration

	SME		LE		
	M	SD	M	SD	ΔM
Sharing information with purchasing	3.39	1.01	3.70	0.94	−0.31**
Joint decision making with purchasing	3.31	1.01	3.60	0.98	−0.29**
Sharing information with sales department	3.35	1.02	3.68	0.99	−0.33**
Joint decision making with sales department	3.23	1.05	3.50	1.07	−0.26**
Sharing information with key suppliers	3.04	0.99	3.45	0.93	−0.41**
Developing collaborative approaches with key suppliers	3.04	1.02	3.33	0.93	−0.29**
Joint decision making with key suppliers	2.80	1.05	3.21	0.99	−0.41**
System coupling with key suppliers (e.g., *VMI, JIT*)	2.59	1.14	3.07	1.11	−0.48**
Sharing information with key customers	2.88	1.07	3.23	1.08	−0.34**
Developing collaborative appr. with key customers	2.76	1.16	3.09	1.10	−0.34**
Sharing information with key customers	2.89	1.12	3.23	1.12	−0.34**
Joint decision making with key customers	2.48	1.23	2.97	1.21	−0.49**
System coupling with key customers (e.g., *VMI, JIT*)	3.39	1.01	3.70	0.94	−0.31**

provide direct links between internal work-groups, such as manufacturing, design, and testing, and external workgroups, represented by suppliers and customers" (p. 9). Similarly, the three fundamental MC capabilities proposed by Salvador et al. [8], i.e., solution space development, choice navigation, and robust process design, rely heavily on the four integration types included in this paper. Integration with customers during design efforts is necessary to identify the product attributes along which customer needs to diverge (solution space development) and to ensure a minimum level of complexity and burden of choice when customers identify their final solution (choice navigation). In particular, an in-depth and continual understanding of consumer preferences is needed for the firm to develop customizable product concepts. Afterward, design integration between manufacturing and product development is required to combine this knowledge of consumer preferences with knowledge about technical product constraints, engineering parameters, and process capabilities. In other words, both customer and design integration are essential for the mass customizer to translate product concepts into feasible product families that can be manufactured efficiently and effectively. The other two types of integration, i.e., supplier and internal integration, are needed to ensure that organizational and value-chain resources can be reused and recombined according to a stream of differentiating needs (robust process design). Increasing the integration with suppliers and internally across purchasing, design, manufacturing, and sales helps mass customizer create processes and products that can accommodate the demanded product variety and customization without impairing the firms' operations. Further, the continual cross-functional and cross-boundary communication also helps make sure that the operations can adjust to changes in demand in a timely manner.

The results indicate that the LEs have indicated a significantly higher level of design, internal, supplier, and customer integration than SMEs. As the difference between LEs and SMEs is pervasive in all the items reflecting integration, it might be difficult for the SME to assess where and how to start increasing their levels of cross-functional and cross-boundary integration. Ismail et al. [27] suggest that SMEs should start their MC process in the design domain and create product families that maximize the reuse of components. By creating an explicit product architecture, the SME can establish the basis for integration, as they have a common language and clear design rules to refer to during inter-functional and intercompany communication. Another way for the SME to approach integration and MC is through the use of advanced manufacturing technologies such as CAD, CAM, and CAPP [9], especially since the advance of these technologies has been seen as one of the reasons why the MC paradigm emerged in the first place [23]. Evidence also indicates that SMEs can utilize advanced manufacturing technologies to increase their operational and business performance, but that this depends on the successful mastering and integration of these technologies, which in turn depends on the education and experience of the owner-manager, the aggressiveness of the firm in developing new markets and technologies, the type of production process employed in the firm, as well as how dependent the firm is on major customers [28].

4.3 Organizational, Manufacturing, and Quality Action Programs

The limited amount of human, time, and financial resources available to the average SME can make it difficult for these firms to invest in the many action programs needed to support MC. This paper analyzes whether there is a difference between the degree to which SMEs and LEs have implemented such MC-enabling action programs in the areas of organization, quality management, and manufacturing.

Successful MC requires the firm to transform their organization. Lui et al. [29], for instance, suggest that the high product variety and high process flexibility inherent to MC will increase the probability of variance in manufacturing. To ensure the timely control of variance and, in turn, support the firm's ability to adopt MC, the authors propose the use of two work design principles, i.e., "feedback to shop-floor employees" and "autonomous maintenance" [29]. Similarly, Tu et al. [30] suggest that shop-floor involvement is necessary to support MC. Further, Pine et al. [2] propose continuous improvement to be a prerequisite of mass customization, that is, the company must first achieve a combination of high quality and low costs, before seeking to achieve higher levels of customization. Pine et al. [2] also note that "even a company that has mastered continuous improvement must change radically the way it is run to become a successful mass customizer" (p. 112). More specifically, they argue that the company must break up the long-lasting cross-functional teams built for continuous improvement and instead create autonomous teams that can interact to make a product/service in response to customer needs. These autonomous teams are enabled by team-based compensation and overlapping and general job descriptions. Kotha [23] adds that for mass customizers, "success is more likely when the firm focuses on knowledge creation and the development manufacturing capabilities" (p. 39) and when "the firm has access to a group of highly trained, disciplined, and motivated workers" (p. 39). To harness the knowledge of individual workers, the case company that Kotha [29] studies uses quality circle programs, ranking of skills, and rotation of highly skilled workers.

In terms of creating a manufacturing and quality management setup that supports MC, the literature also is abundant. Tu et al. [30], for instance, find a positive link between MC and the adoption of time-based manufacturing practices such as cellular manufacturing, preventive maintenance, quality improvement efforts, and pull production. Cellular manufacturing, i.e., consolidating processes into cells that are designed to process parts with similar design features [30], is closely related to process modularity, one of the main enablers of mass customization [3]. More specifically, cellular manufacturing enables the creation of process modules that can be decoupled and re-sequenced according to customer demand. Using pull production also supports mass customization, as it supports close coupling of demand and production [30]. In fact, authors propose mass customizers to use postponement in order to combine cost-efficient push production of modules with responsive pull production used during the final assembly stages [31].

MC manufacturing environments are likely to have a higher amount of variance. Compared to mass manufacturing, MC production is likely to be conducted in smaller batches, where at least a portion of the components produced will be variable, making setup times and processes vary more and less easy to predict. Furthermore, the continual design and development of new products to match evolving customer needs is likely to result in frequent engineering changes [32]. This relative higher variance and uncertainty in production requires the mass customizer to adopt practices that ensure that a minimum amount of variance is attributable to unreliable machines and processes, i.e., practices related to quality improvement and equipment availability.

Having controlled processes and machines, however, does not mean that the remaining variance and uncertainty inherent to the MC production system can remain unchecked. More specifically, MC systems also require proper planning and control of production as well as a constant flow of information between internal functions and with external partners [32]. This is achieved by, among others, engaging in part tracking and tracing, implementing techniques to improve forecasting and planning accuracy, and monitoring and controlling production through a dedicated manufacturing system. In order to accommodate the variety of products, demand fluctuations, and the continual introduction of new products, the manufacturing system must also have an innate level of flexibility. Therefore, "factory of the future" practices such as scalable and adaptive manufacturing are very relevant for firms wanting to mass customize their products and processes [35].

All in all, the majority of the action programs listed in Tables 12, 13, and 14 can contribute to the successful implementation and management of MC. However, when compared to LEs, SMEs have a lower level of implementation of all but one of these action programs. Therefore, the same question emerges as before, where and how should SMEs start to ensure that they have an organizational and manufacturing

Table 12 Organizational action programs

	SME		LE		
	M	SD	M	SD	ΔM
Delegation and knowledge of your workers (e.g., *empowerment, training, improvement incentives*)	2.93	0.94	3.30	0.93	−0.38**
Open communication between workers and managers (e.g., *information sharing, bottom-up communication*)	3.41	1.02	3.62	0.92	−0.21**
Lean organization (e.g., *few hierarchical levels*)	3.10	1.09	3.42	0.99	−0.32**
Continuous improvement programs (e.g., *kaizen, improvement team, improvement incentives*)	2.93	1.07	3.59	0.96	−0.67**
Autonomous teams (e.g., *workgroup incentives, teams responsible for planning, execution, and control*)	2.75	1.08	3.11	1.07	−0.36**
Works flexibility (e.g., *multitasking, multi-skilling*)	3.34	0.93	3.40	0.95	−0.06
Use of flexible works of work (e.g., *temporary workers, job sharing, variable working hours*)	2.80	1.18	3.02	1.16	−0.22**

Scale: Current level of implementation from 1 (none) to 5 (high). The same scale is used in the remaining tables

Table 13 Quality action programs

	SME		LE		
	M	SD	M	SD	ΔM
Quality improvement and control (e.g., *TQM programs, six sigma projects, quality circles*)	2.99	1.15	3.56	0.97	−0.57**
Improving equipment availability (e.g., *total productive maintenance programs*)	2.86	0.97	3.36	1.00	−0.50**
Benchmarking/self-assessment (e.g., *quality awards, EFQM model*)	2.42	1.15	3.10	1.13	−0.67**

setup that support mass customization? Successful MC could start off with organizational and quality-oriented programs, such as continuous improvement, total quality management, six sigma, and total productive maintenance. Using these programs and simultaneously increasing worker flexibility and communication between the shop floor and management would create an organization with controlled processes and a knowledgeable workforce, more capable of accommodating change. This is in line with Pine et al. [2], who suggest that, in order to minimize the variance and uncertainties attributable to processes, equipment, machines, and human error, firms striving toward MC must start off with continuous improvement and quality management.

However, one could also argue that the correct approach to MC depends on the amount of change needed to the manufacturing processes. If it requires the manufacturer to invest in new machinery, it is a meaningless exercise to focus on the continual improvement of existing procedures and processes. In other words, if the SME needs to adopt technology to increase the flexibility of their manufacturing setup, these organizational and quality-oriented programs are likely best implemented afterward. A third option is that SMEs should, in the beginning

Table 14 Manufacturing action programs

	SME		LE		
	M	SD	M	SD	ΔM
Restructuring man. processes and layout to obtain process focus and streamlining (e.g., *cellular layout*)	3.07	1.08	3.63	0.89	−0.55**
Undertaking actions to implement pull production (e.g., *reducing batches and setup times, Kanban systems*)	2.86	1.12	3.47	1.00	−0.61**
Improving forecasting and planning accuracy (e.g., *methods, software, frequency*)	3.00	1.07	3.43	0.91	−0.44**
Increasing information integration (e.g., *monitoring and control through a dedicated information system*)	3.03	1.10	3.29	1.02	−0.26**
Engaging in product/part tracking and tracing programs (e.g., *bar codes, RFID*)	2.62	1.25	3.18	1.15	−0.57**
Use of advanced processes (e.g., *laser and water cutting, 3D printing, high precision technologies*)	2.59	1.30	2.99	1.29	−0.40**
Development toward "the factory of the future" (e.g., *scalable and adaptive manufacturing*)	2.21	1.10	2.78	1.12	−0.56**
Engaging in process automation programs (e.g., *automated machine tools and handling equipment*)	2.58	1.25	3.11	1.16	−0.53**

of the MC journey, start off with improving their product design [27] and first then design their processes accordingly, after which they can implement mechanisms that ensure the continual development of these processes.

5 Conclusions and Further Research

As expressed by Welsh [33], "A small business is not a little big business." There are fundamental differences between SMEs and LEs, i.e., SMEs typically have fewer resources, a narrower span of activities, flatter organizational structures and pursue informal, reactive strategies often dictated by the central manager/owner [12, 19, 20].

Though these differences are well-established, the majority of MC literature is directed at or based on evidence from large enterprises and does not address whether and how SMEs can achieve successful MC (see, for instance, [1–4]). In this LE-oriented MC literature, the emergence of the MC paradigm is explained by environmental changes and the development of new technologies, which enables the mass manufacturers to react to these changes and use mass production techniques to achieve the low-cost production of individually customized products [23]. The question is whether these environmental changes are specific to LEs only and, if not, whether and how SMEs also can adopt MC-related technologies and practices to successfully deal with these environmental changes.

To help answer this question, this paper uses data collected via an international survey and first compares how SMEs and LEs perceive their environmental dynamics and competitiveness. The results of the independent sample t-test indicate that, compared to LEs, SMEs have smaller market spans, experience lower rates of technological change, and have less competitive rivalry. However, there are no significant differences between the two types of firms when it comes to the other competitive forces (bargaining power of suppliers and buyers and threat of new entrants and substitutes) [24] as well as the degree to which the firms experience different types of fluctuations. Therefore, this paper concludes that from the perspective of the external environment, MC indeed seems as a valid strategy for both LEs and SMEs in order to cope with fluctuations and attain a competitive edge.

The next step in this paper was to compare the LE and SME subsamples with respect to the degree to which they (1) have implemented mechanisms supporting design, internal, and external integration and (2) have implemented MC-related organizational, manufacturing, and quality practices. Design, internal, and external integration is important for successful MC as it enables an in-depth and continual understanding of consumer preferences, the translation of these consumer preferences into feasible product options, the translation of customer choices into resulting product configurations and manufacturing instructions, and the management and control of manufacturing so that the inherent complexity and uncertainty of MC manufacturing does not impair operational efficiency [8, 9]. Since MC manufacturing is characterized by a relatively higher uncertainty and variance when compared to typical mass manufacturing [29], other practices in the area of manufacturing, organization, and quality have been proposed to help manage and minimize the variance and uncertainties caused by machine, equipment, or human error or deviations in processes and procedures. This includes practices related to continuous improvement [2], time-based manufacturing [30], knowledge management [23], work design [29], and so forth. In addition to being able to cope with uncertainty and complexity, the manufacturing processes should also be flexible and responsive in order for the firm to be able to produce customized products quickly and efficiently. Therefore, the literature also proposes a plethora of MC-enabling practices that increase manufacturing flexibility and responsiveness including "factory of the future" practices such as scalable or adaptive manufacturing [35]; practices supporting the creation of modular processes such as postponement [3], pull production [30], and cellular manufacturing [30]; and practices that increase worker flexibility such as multitasking and multi-skilling [23].

With the exception of practices supporting worker flexibility, the findings of the survey indicate that SMEs lag behind LEs in the adoption of all practices, both in term of practices supporting design, customer, and supplier integration and in the adoption of MC-related organizational, manufacturing, and quality practices. As the differences between SMEs and LEs are so persistent and the financial and human resources of SMEs are limited, the question is where and how should SMEs start when pursuing MC. Reviewing existing literature, this paper points toward some potential starting points, including:

- The standardization of the product portfolio, so that the SME effectively applies the limited amount resources currently available to them [27]. Practices such as product modularization, platform thinking, DfX methods, and product family planning can form the basis for managing the negative impact of product variety on internal operating performance and also help establish clear rules about component interaction through an explicit product architecture, which creates a common language supporting inter-functional and intercompany communication and collaboration [27, 34].
- Investing in advanced manufacturing technologies, which, if mastered and integrated appropriately, have proven to have a positive effect on SME operational and business performance [28]. The successful integration and assimilation of these technologies depend on, among others, the education and experience of the owner-manager, the aggressiveness of the firm in developing new markets and technologies, the type of production process employed in the firm, as well as how dependent the firm is on major customers [28].
- The creation of an organization geared toward continuous quality improvement in order to minimize the variance and uncertainties attributable to processes, equipment, machines, and human error [2].

Whether one of these or another starting points is the appropriate one for SMEs is a topic for further research. However, in all likelihood, there is no one-size-fits all solution for achieving MC in SMEs. Further research should, therefore, not only focus on determining the mechanisms and methods by which SMEs can begin their path toward successful MC but also identify key internal and external SME characteristics that influence whether and how the SME should pursue MC.

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Productivity, Challenges, and Applying Mass Customization in the Building and Construction Industry

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Abstract The productivity in the Danish construction industry is significantly less compared to other sectors in Denmark. It has only doubled over the last 50 years, and based on this fact, this paper as a starting point look into the productivity of the building and construction industry to investigate trend similarities with other countries. Hereafter a literature study elaborates the challenges within the building and construction industry to understand the conditions that strain the industry in improving productivity.

Mass customization as a strategy has increased productivity and competitiveness in other industries in Denmark, and despite that mass customization has not been explored much in the research field of the building and construction industry, so implementing this strategy might affect the building and construction industry in a positive way. Therefore, this paper also study some indicators that justify mass customization as a strategy applicable within the building and construction industry, as well as some assumptions and requirements of applying mass customization.

Keywords Mass customization · Construction industry · Productivity

1 Introduction

The global marketplace is putting pressure on companies to stay competitive, leading to various continuously improvement programs combined with complying customer requirements by offering more and more opportunities in the sense of customization, individualization, and personalization.

However, customers still require attractive sales prices, optimal deliveries, and service conditions; therefore companies introduce new products faster and faster and strive to improve initiatives for cost and delivering efficiency as these are

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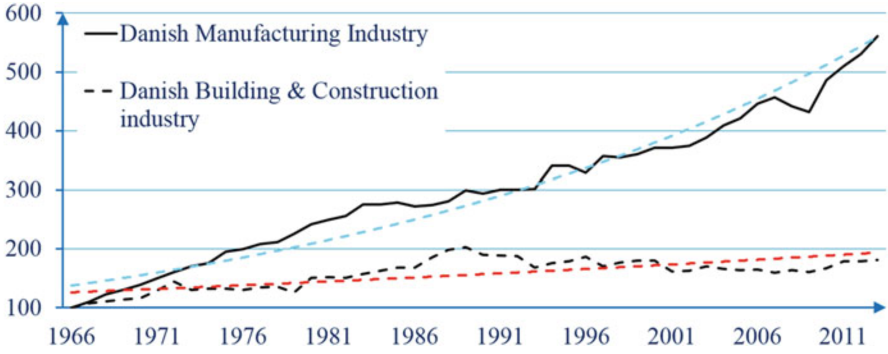

Fig. 1 Labor productivity (index 1966 = 100). (Statistics Bank NATP23)

conditions necessary for manufacturing companies in order to stay competitive. The same conditions are affecting the building and construction industry that also is facing productivity issues compared to other industries. Therefore, companies make great effort to achieve initiatives of reducing production costs focusing on, e.g., lean construction, Six Sigma, TQM initiatives, and standardization.

The performance of the building and construction industry has been lacking compared to other industries, and the productivity in the Danish building and construction industry that employs approx. 25% [4] of the private workforce in Denmark has only doubled since 1966 [9] (Fig. 1). Productivity is measured as output per performed working hour for the entire Danish economy [9]. The manufacturing industry has in the same period increased the productivity almost six times, and some have handled the customer requirement of higher product variety at an efficiency cost level by adopting the mass customization strategy, which could have contributed to the increasing productivity.

The building and construction industry has a lower degree of industrialization compared to the manufacturing industry, and the reasoning is that most products and projects are characterized as “one of a kind,” which may seem challenging to optimize processes [1, 3], as the industry seems very conservative.

The industrial production has gone through a process by offering customized products [39] “at prices near mass production [1]” by application of mass customization as a strategy [27] that focuses on offering customized products at a low cost, by utilizing enablers like product modularity, process modularity, supply chain modularity, standardization, postponement strategy (decoupling point), configuration tools and flexible manufacturing systems, etc. [24].

The demand for customization within the building and construction industry is difficult to handle with traditional industrialization initiatives [15] like standardization and mass production, and the customers seem to be more selective and demanding by requiring what they want, when they want it, and where they want it [13], which is the challenging edge of the building and construction industry.

Mass customization as a strategy focuses on delivering of customized products [27] by handling the requirement of flexible products, processes, and supply chains efficiently; thus it seems reasonable for the building and construction industry to apply the principles of mass customization, as the building and construction industry faces challenges in developing and producing high variety products, often one of a kind [7].

This paper addresses the productivity of the building and construction industry to see if there are trend similarities with other countries or if the abovementioned productivity development (Fig. 1) is a Danish phenomenon. Hereafter a literature study elaborates the challenges within the building and construction industry to understand the conditions that strain the industry from improving productivity. This paper also studies some indicators that justify mass customization as a strategy applicable within the building and construction industry, as well as some assumptions and requirements of applying mass customization.

2 Productivity Trend Similarities

Labor productivity is generally considered as the output per hour worked, which is one of the best indicators of production efficiency meaning that higher productivity levels usually correspond to profitability excellence. Sustainable improvements in labor productivity are in capitalist market-driven societies associated with economic progress as it generates noninflationary increases in salaries and wages.

Calculating productivity values for an industry requires three variables: the industry's output, the industry's employment data, and the average number of hours worked, so mathematically the productivity is calculated as [32]:

$$p_i = \frac{\mathrm{GPO}_i}{\sum_{j=1}^{12} E_{ij} H_{ij}}$$

where P_i = labor productivity for industry i; GPO_i = gross product originating by industry for industry i; E_{ij} = average number of employees for industry i in month j; and H_{ij} = average number of hours worked for industry i in month j. Gross product originating by industry (GPO) is the contribution of each private industry and government to the nation's output, or gross domestic product (GDP).

The relationship between labor productivity in the building and construction industries and the manufacturing industries has been problematic or different in Denmark the last 50 years, and as seen in Fig. 1, both lines have during the period increased and the slope of the line has more or less been the same with a slight progressing trend for the manufacturing industry. The slope difference may be due to many different circumstances caused by national or industry traditions. However, according to further research and improvement initiatives, it is interesting to know if the trend is national or industry specific, so the investigation focused on data, graphs, and materials available for countries with uniformity and diversity; therefore countries in Scandinavia and Europe are included. The countries are prioritized in this order but selected randomly based on data available as the investigation at this point is mostly focusing on finding indications or trend similarities.

The following countries are a part of the investigation of similarities between the Scandinavian countries [17]: Finland, Denmark, Sweden, and Norway, with whom Denmark in many ways is comparable due to common historical roots, cultural conditions, and common collaboration traditions and other aspects. Figures 2 and 3 indicate similarities for all countries in Scandinavia in terms of a significant gap of the productivity development between the construction industry and manufacturing industry.

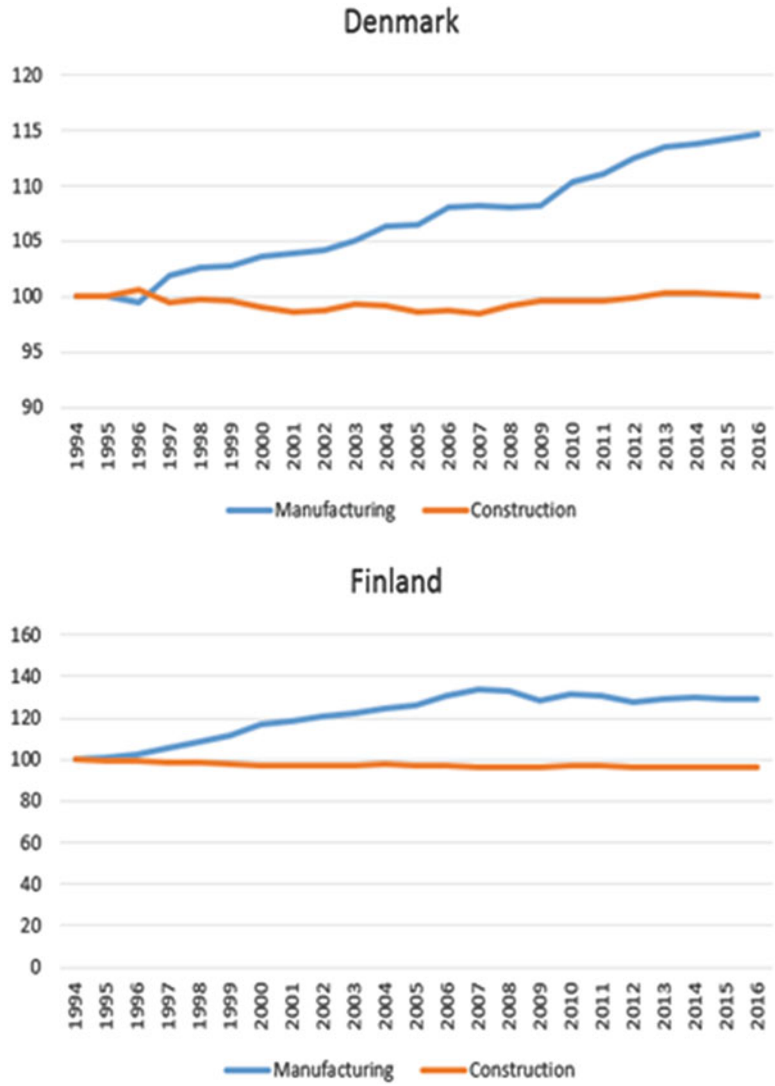

Fig. 2 Productivity development in Denmark and Finland (Source: OECD stat)

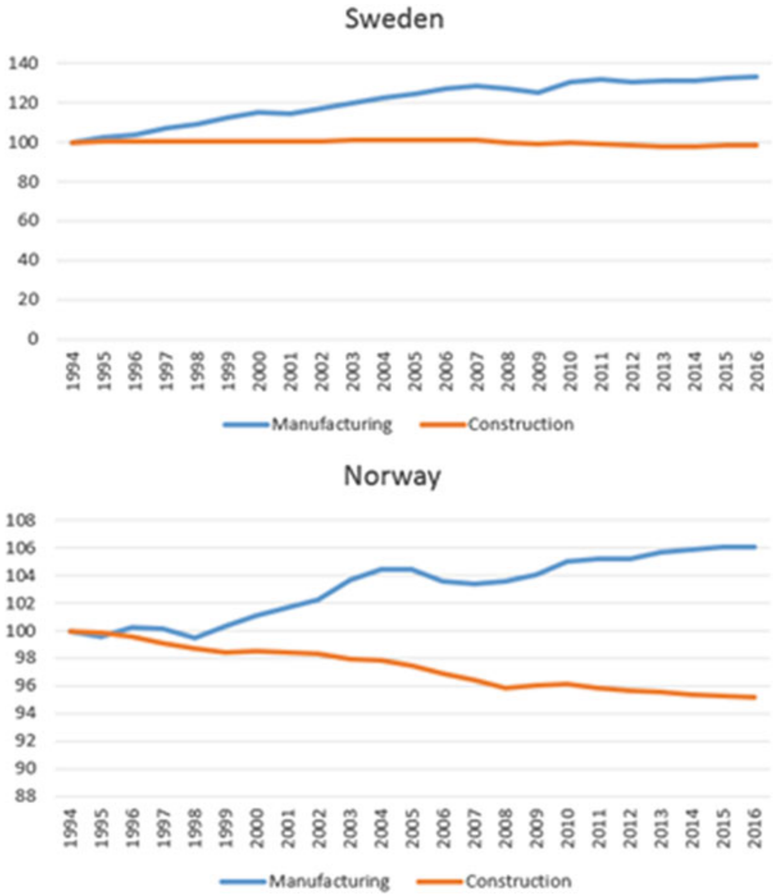

Fig. 3 Productivity development in Sweden and Norway (Source: OECD stat)

Looking at the countries in Europe from best- and worst-in-class perspectives for the manufacturing industry and the construction industry, respectively, it is evident that Latvia has gone through the highest construction productivity increase (index 103) during the period of the last 15 years (2001–2016) and Norway has gone through the lowest construction productivity, actually a decrease (index 97). For both countries a significant gap exists between manufacturing industry and construction industry (Fig. 4).

Hungary is the best in class concerning manufacturing productivity increase (index 125). Luxemburg has achieved the lowest manufacturing productivity increase (index 101). For Hungary a significant gap exists between manufacturing industry and construction industry, which is not the case for Luxemburg as the gap is limited (Fig. 4). It has to be noted that the countries' starting point of the absolute productivity is not necessarily the same, which means that the percentage improvements can be more readily achievable to someone than others.

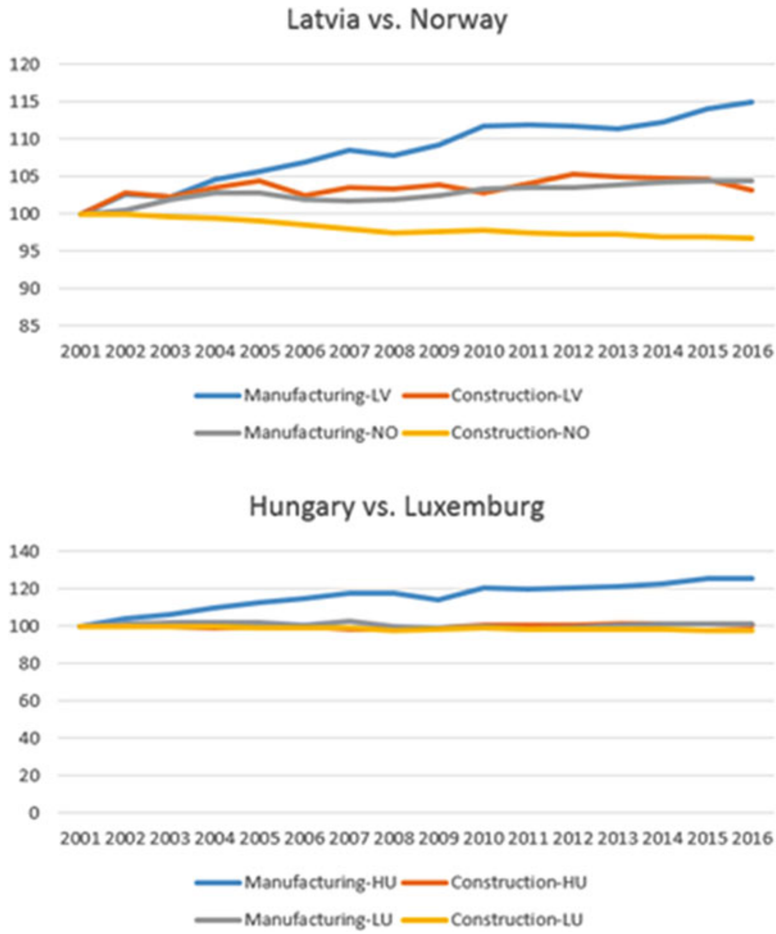

Fig. 4 Best and worst in class for manufacturing and construction, respectively. (Source: OECD stat)

Investigating all countries in Europe as a whole, Fig. 5 shows that Denmark is very similar to Europe concerning the development of productivity for manufacturing companies and construction companies for the last 20 years.

That means that the initial observation (Fig. 1) concerning the productivity gap between the building and construction industry in Denmark and the manufacturing industry in Denmark is not a Danish phenomenon, but characteristics applicable in almost all countries in Scandinavia and Europe. The same trends are seen in Canada and the USA, which indicate that this is a worldwide phenomenon or challenge.

"Poor management practices that lead to poor performance such as changes in scope, errors in design and omission of details, lack of adequate planning and scheduling, poor management of tools" [23] have been identified as factors

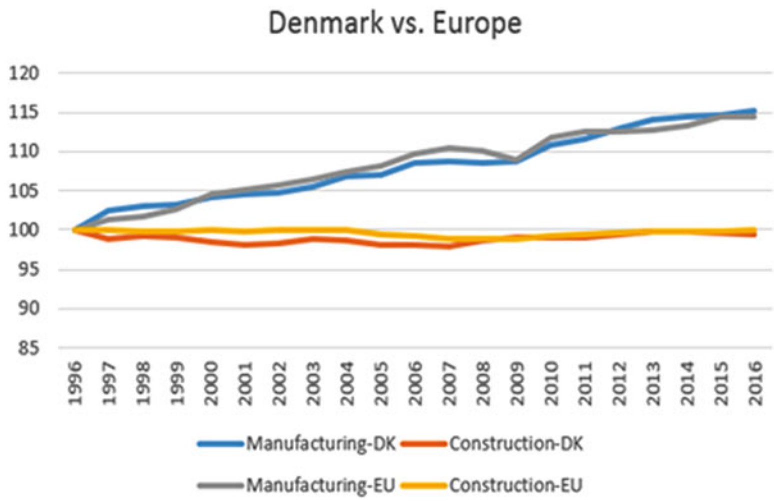

Fig. 5 Productivity of Denmark vs. Europe. (Source: OECD stat)

impacting productivity. However, the productivity gap between construction and manufacturing industry might be due to potentially common reasons based on the stated country similarities. Therefore, it is obviously necessary to look at the challenges in the building and construction industry.

3 Challenges in the Building and Construction Industry

The Danish, Scandinavian, European, and worldwide productivity gap between the construction industry and the manufacturing industry has been discussed and analyzed widely, and still it is not fully understood why the productivity of construction has flatlined over the last more than 15 years. This initial literature study elaborates the challenges within the building and construction industry to understand the conditions that influent the industry in improving productivity.

A study revealed that practices to increase productivity not necessary are similar in each country, and the study identified different factors influencing labor productivity, which are grouped according to their characteristics such as design, execution plan, material, equipment, labor, health and safety, supervision, working time, project factor, quality, leadership and coordination, organization, owner/consultant, and external factors [30].

Productivity factors causing low productivity can be classified in many ways, e.g., as factors related to the industry, labor, and management. Factors related to the industry are basically the characteristics of the construction industry, such as the singularity and uniqueness of construction projects that often are "one-of-a-kind" projects, which are being built at varied locations and at adverse and unpredictable weather conditions and seasonality. Factors related to labor include the union's influence, safety considerations and legal procedures, potentials for learning, and lack of motivation of engagement and well-being. Factors related to management usually refer to a lack of leadership and management, tools, and technology availability. There seems to exist a common research view indicating that the construction industry is characterized by complexity factors and inefficiency of operations [10] and a number of issues like "poor productivity and profitability," "poor project performance," "skilled labor shortages," "communication problems," and "sustainability concerns," which are among the main issues of interest for improving the construction industry [22, 31, 36].

These factors among others like "poor management" (35.5), "poor communications" (16.2), "low budget or insufficient staff" (12.0), "poor pay or no recognition" (10.0), "lack of training" (8.1), "poor technology" (7.1), "meetings and changes in plans" (6.1), and "too much work to do" (5.0) have in a survey [14] been rated as indicated in brackets (#) as issues all affecting the productivity in building industry.

The building industry is experiencing a lot of challenges and traditions to deal with such difficulties in accurate estimation of lead time and delivery dates, late changes, expensive reworks, unstable weather conditions, and poor product quality [11]. Globalization, margin shrink, increased competition, and dramatic technological advances raise crucial issues concerning the building industry and ETO companies to retain a competitive edge [11, 20, 24].

Many challenges are faced by building and construction industry: some are new to the industry and some are old, known for decades. Many of the challenges are a direct result of construction operations such as cost, time, quality, and changing nature of the work; and others are indirect issues such as environmental, sociopolitical, and legal issues and government regulations [25]. Understanding and dealing with these demanding realities is critical in the planning and control of building and construction operations, which is represented by a set of activities that must take place to produce a unique custom-specific product. The success of such a project is determined by the extent to which the criteria of cost, time, security, resources, and quality are met by the owner in a manner that generates an appropriate profit with which productivity can be improved.

A well-known integrated process involving parties of the building and construction industry assuring activities around "product development," "project implementation," "partnering the supply chain," "production of components," etc. takes place properly and appropriately. However, the building and construction projects are complex often felt with many unforeseen and unpredictable issues to deal with in comparison to the manufacturing industry, e.g., weather and environmental conditions, seasonal work, remote sites with different accessibility, and difficulty in applying atomization.

However, excellent project management and leadership is to understand and navigate through these realities whether they are direct or indirect building and construction issues. Transforming risks into opportunities and mastering common project management disciplines by focusing on the overall purpose, which is to achieve goals and objectives through the budgeted amount of resources and deliverables to meet the quality, cost, and time, scope, and safety requirements. This includes preparing for and mitigating the effects of any unforeseen situation that could affect the project success described by the finished product and its functionality, its cost, its quality, and the ability of being delivered on time.

4 Applying Mass Customization

It seems reasonable for the building and construction industry to investigate the principles of mass customization as a strategy for productivity improvements. Firstly, the building and construction industry focuses on delivering customized products; secondly, mass customization is a strategy for handling customizable product requirements efficiently; and thirdly, mass customization has increased productivity and competitiveness in the manufacturing industry in Denmark.

Mass customization is a competitive strategy for mass production companies transitioning from one state to another by focusing on providing individually products and services to customers trying to optimize the unit cost/customer value ratio [29] or "producing goods and service to meet individual customers' needs at near mass production efficiency" [38]. In order to stay competitive, companies within the supply chain must respond to global challenges and efficiently offer a wide range of products fitting different customer needs and continuously including new product technologies and product models [16, 19]. Mass customization is a strategy for configuring individually products delivered at a low cost [13, 28, 35], and research indicates that companies utilizing mass customization must have three fundamental capabilities [35]:

1. "Solution Space Development: the ability to identify how customer requirements are different and develop products that can effectively adapt to these individual requirements through the product platforms or modularization"
2. "Choice Navigation: the ability to guide the customer to select or configure the product that matches these requirements"
3. "Robust Process Design: the ability to efficiently produce a large batch of products at low cost that typically is achieved by using the flexible manufacturing systems"

The three capabilities are not to be understood as finite transition destinations, rather as a guidance for a journey toward profitability serving customer demands by designing products, processes, and value chains and meeting customer demands individually [29]. Indeed, there is no "perfect" state of mass customization [35], so what suits one company might not necessary be suitable for another company; therefore the development possibilities and the transition initiatives might be individually (Fig. 6).

"Solution Space Development" is the capability of identifying the solution needs of its customer, trying to define the differences and preferences of the customer needs, and clarifying what the company will offer and what it will not. The starting

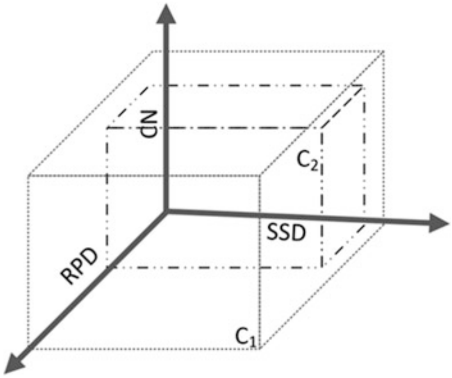

Fig. 6 Ratio of the three capabilities: Robust Process Design (RPD), Choice Navigation (CN), Solution Space Development (SSD) of mass customization for company C_1, C_2

point is a knowledgebase of preferences, solution needs, key desires, and satisfaction motives of the potential customers and users of the products or services.

"Choice Navigation" is how the mass customizer supports their customer in the decision phase by identifying their needs and specifying and presenting the wanted solution. The existence and ongoing development of effective and user-friendly product configuration tools [12] are providing the customers with features and options for decision making and illustration possibilities to clarify the end product and services. The essential part is to offer just enough features and options as too many can confuse and reduce the customer value [8] and can postpone the buying decision.

"Robust Process Design" is the capability of focusing on reusing existing organizational and value-chain resources handling the increased variability in customers' requirements without significantly influencing the operational efficiency and reliability [28].

A higher level of customization often leads to a higher resource consumption as a consequence of complexity in processes; unpredictability in planning and production caused by larger product variety, greater number of parts, more processes, and more suppliers, retailers, and distribution channels; etc. Stability, flexibility, and responsiveness in the business processes around handling the variance of products and services are some of the characteristics of a well-functioning mass customization system [26, 34].

However, the objective is to minimize the additional cost and still serve the customers individually by applying some appropriate techniques like delaying product differentiation, utilizing flexible automation technology, utilizing modularity in products and processes, and utilizing information and communications technology (ICT). Available technology supports companies in delivering what customers want, and ICT tools support the handling process, so the end customer can select options matching unique requirements at low prices [7, 27]. Automated business processes, product configurators, and product design are used with great success in, e.g., automotive and computer industry [27, 35].

A research project [18] concerning mass customization in the Danish building and construction industry aims at making companies capable of understanding

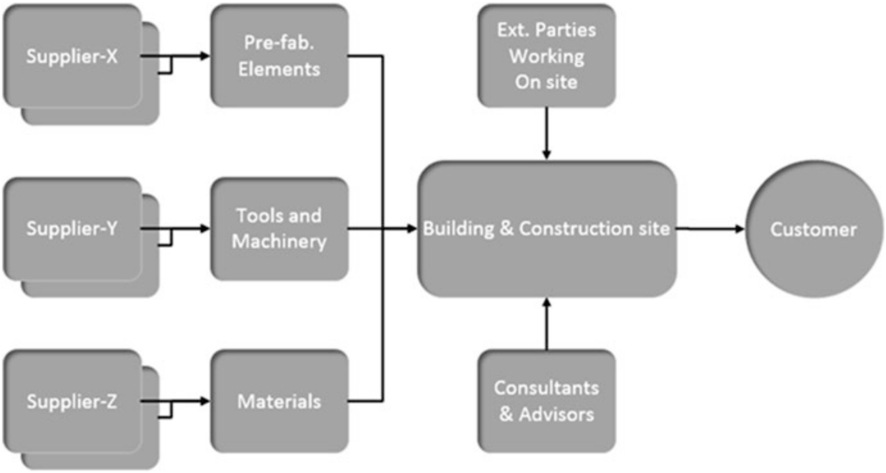

Fig. 7 Parties of the building and construction value chain

the principles of mass customization, and the participating companies all indicate a trend toward more customized products and are planning to be more mass customization oriented [18]. Some companies supplying the building and construction industry, e.g., manufacturers of windows, doors, kitchen, housing, and bath products, have successfully implemented parts of mass customization [2, 6].

Application of mass customization in a broader perspective between actors of the value chain (Fig. 7) focusing on unified communication seems possible by using ICT, and an approach to any building and construction projects can only be achieved where the customer needs are integrated across the design process [5]. A research project [40] from a Dutch house building industry stated three modularity dimensions: product modularity, process modularity, and supply chain modularity, which implies integration within the supply chain by incorporating responsiveness to changes and variety of product demands, quantities, and delivery demands [37, 40].

Engineer to order (ETO) is a manufacturing strategy aiming at providing highly customized products, which are to be designed, developed, and engineered in a close cooperation with the customer based on detailed information, requirements, and specifications from the customer. Highly specialized customer requirements pose various challenges, e.g., difficulties in estimation of delivery dates; handling late changes, reworks, etc.; and at the same time trying to meet the requirements coming from the increased globalized competition and new technological possibilities [11]. The “Solution Space Development” for ETO companies like the building and construction companies is to be understood as the solution boundary representing the products and services available for customers, where some might be standard products and some might be nonstandard products, but with known limitations of what to be offered and delivered to the customers.

Most literature about mass customization focus on companies' transition from mass production to mass customization, so as ETO companies are positioned opposite in the customer order decoupling point (CODP) [33], there might be major differences between mass production and ETO companies in their transition toward mass customization, even though a research indicates that it is reasonable to label some ETO companies as mass customizers although the end products are not at prices near mass-produced ones, as many popular definitions of mass customization claim [15].

Hence, mass customization as a strategy is applicable for more or less all parties (Fig. 7) seen from a company's perspective individually, so the interesting viewpoint is to investigate the assumptions and requirements of applying mass customization successfully between all parties within the building and construction chain (Fig. 7).

Standards and ICT tools for smooth integration and collaboration are some of the cornerstones of applying mass customization successfully across members of the value chain, and Industry Foundation Classes (IFC) is the core of five open standards representing an environment of interoperability among compliant software applications in the architecture, engineering, construction, and facilities management (AEC/FM) industry. These five open, formal, and international standards are designed to enable horizontal compatibility between AEC and FM software applications [21] and represent open specifications for Building Information Modeling (BIM) to be exchanged and shared among parties (Fig. 7) describing geometrics, concepts, quantity, actors, cost, material, and data specification items related to the building construction and facility management projects for collaboration purposes. An example could be that the architect initiates the project by making a high-level drawing framing the construction so the customer could recognize and accept the project idea. The information necessary are delivered to the parties (Fig. 7) involved in the project, so they know about the boundaries about the building requirements of parts, properties, units, and values, function of the spaces in the building, dimensions and specification, and other collaborations issues. The receiving companies verify the data and get started utilizing own software, which might be unique for the specific company's role and purpose in the value chain (Fig. 7). Engineers fulfill their contribution of the combined work, e.g., calculating, dimensioning, detailing drawings, and making comments, and the enriched information are sent back for further collaboration purposes.

It seems that existing standards like IFC among others can improve the possibilities of cooperation between parties (Fig. 7) across the supply chain obtained from cradle to grave of the building and construction project. Proper commitment between parties, requirements of data discipline, information management, and coordination of models throughout the entire project are critical for a successful corporation, and thereby the application of mass customization within the building and construction industry is a strategy for improving the productivity.

However, it seems that mass customization is applicable and used by the members individually of the supply chain (Fig. 7) in regard to improving productivity. Mass customization together with ICT and IFC standardization initiatives as described seems to indicate that it makes sense to utilize mass customization as a strategy improving the productivity within the building and construction industry (Fig. 7) and as an integrated system responding to the three capabilities of mass customization [35].

5 Conclusion

This paper addresses three main topics related to the building and construction industry: firstly, productivity similarities between Denmark and other countries; secondly, challenges in the industry; and thirdly, the usability of mass customization as a strategy.

Based on the fact that the productivity in the Danish construction industry has only doubled over the last 50 years, which compared to other sectors in Denmark is significantly less, this paper investigates trend similarities of countries with uniformity and diversity in Scandinavia and Europe. The investigation showed similarities for all countries in Scandinavia and Europe in terms of a significant gap of the productivity development between the construction industry and manufacturing industry.

A literature study investigates the challenges within the building and construction industry to understand the conditions that strain the industry in improving productivity. Common research view indicates that the construction industry is subject to complexity factors, such as inefficiency of operations like “poor productivity and profitability,” “poor project performance,” “skilled labor shortages,” “communication problems,” and “sustainability concerns,” which are among the main issues affecting the building and construction industry. Many of the challenges are a direct result of the operations (cost, time, quality, and changing nature of the work), and others are indirect issues (environmental, socio political, and legal issues, government regulations). However, the projects are complex having many unforeseen and unpredictable issues in comparison to the manufacturing industry, e.g., weather and environmental conditions, seasonal work, remote sites with different accessibility, and difficulty in applying atomization. Nevertheless, it is a necessity to understand and deal with these demanding realities (direct or indirect) to be successful by transforming risks into opportunities and mastering common project management disciplines, which implies having integrated processes involving parties of the building and construction industry assuring activities around “product development,” “project implementation,” “partnering the supply chain,” “production of components,” etc.

This paper also studies some indicators that justify mass customization as a strategy applicable within the building and construction industry, as well as some assumptions and requirements of applying mass customization. The paper indicates some challenges related to establishing an adaptable integrated system between parties by applying the principles of mass customization with focus on the three capabilities: “Choice Navigation,” “Robust Process Design,” and “Solution Space Development.” An essential part is the conditions for cooperation between the parties, where ICT and IFC are a necessity of the cooperation possibilities around projects. Obviously the information exchange between parties is possible in a standardized and global-oriented way aiming at a total cost reduction of maintaining the database of material, products, and elements used between parties.

The IFC standardization initiative together with mass customization as a strategy seems possible for improving the inefficiencies within the building and construction industry. A prerequisite for success is software development and incorporation of the necessary standards effectively to be used by all the involved parties supporting their role individually by contributing to the whole workflow of a project.

The continuous software and standard development indicates possibilities of applying and benefit of mass customization as a strategy for parties in the building and construction industry; however the initiatives and transition depend on further research. However, it seems to include other benefits like quality improvement by proper and timely exchange of knowledge and information between parties to ensure compliance with the basic requirements, which substantiates the potentials for productivity improvements.

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Flexibility in Mass Customization of Houses

Salman Khalili-Araghi and Branko Kolarevic

Abstract Mass customization as a business strategy serves to provide for product variations while maintaining the efficiency of production. Houses are one-of-a-kind products that reflect social and cultural differences of inhabitants who live in them. True adaptation of mass customization in the housing industry demands for flexibility, that is, stability and responsiveness in producing highly customized houses. Achieving that requires smooth flow of information among and effective collaboration between customers, designers, and manufacturers. This paper presents a comprehensive framework in the adaptation of mass customization in the housing industry by delineating fundamentals and technological developments in design, customization, and manufacturing spaces. Difficulties and challenges of such an approach are discussed from both companies' and customers' perspectives.

Keywords Mass customization · Housing industry · Customer participation · Configuration toolkits

1 Introduction

Mass-produced housing, as a necessity for high demand housing, was initially recognized in the twentieth century by focusing on affordability and low-cost production. However, repetitively produced housing was perpetuated as monolithic, and the productivity, quality, and efficiency in mass production did not provide for flexibility and variety. Responding to the heterogeneity of customer demands, mass

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customization can offer promises in design variability with the cost at, or nearly at, that of mass-produced products. As a business strategy, mass customization was initially coined by Stan Davis in which “the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously [. . .] be treated individually as in the customized markets of pre-industrial economies” ([1], p. 169). Similarly, David Anderson describes mass customization as “the ability to satisfy customers with exactly what they want, when they want it, at the lowest cost on the market” ([2], p. 47). Pertaining to the housing industry, mass customization offers promises in satisfying customer demands by producing unique and highly customized houses, that is, one-of-a-kind houses.

Current research delineates a framework for the adaptation of mass customization in the prefabricated housing industry. The research methodology is based on the review of extant literature: first, in the context of mass customization, focusing on definitions, fundamentals, and enablers, and second, in the prefabricated housing industry, focusing on fundamentals and technological innovations, supported by discussion about its limitations and failure factors. To achieve the mentioned goal, this paper is structured as first, presenting an introduction to the housing industrialization; second, delineating fundamentals and technological developments in design, customization, and manufacturing spaces with a focus on the housing industry, which are supported by several industry applications and research directions; and third, presenting challenges and limitations of such an approach, followed by a conclusion and future research.

2 Housing Industrialization

Today, every domain is systemized, and the building industry is of no exception (even as a late comer to the field). System buildings are attributed to the industrialization of construction production: aiming economics of scale with efficiency in delivery time and building cost. Historically, architects and homebuilders such as Le Corbusier, Buckminster Fuller, Walter Gropius, Jean Prouve, and Carl Strandlund looked at the industrial nature of the automobile to deal with the challenge of economy and scope of production. They were fascinated by the concept of assembly line, which was initially developed by Henry Ford in 1913 for the mass production of automobile. In the manifest Toward an Architecture (1922), Le Corbusier refers to a visionary definition of housing that “the house is a machine for living in” ([3], p. 151) and calls mass production “A great era has just begun [. . .] We must create the mass-production spirit. The spirit of constructing mass-production houses. The spirit of living in mass-production houses. The spirit of conceiving mass-production houses” ([3], p. 88).

System buildings refer to the prefabrication (off-site manufacturing) of components that are then delivered to the site and assembled to make a complete product [4]. The basic grammar of prefabrication is standardization, which can result in low production cost and affordability. The utmost advantage of prefabrication is recognized when there is a high demand of production, where the cost of machinery and fabrication can be compromised with economies of scale. A house that is categorized as prefabricated is often misunderstood with having been produced of standard elements, that is, lack in reflecting variety. Prefabricated houses include industrialized standard elements, but not every custom home made of industrialized standard elements necessarily indicates a prefabricated system. The prefabricated buildings, whether they contain industrialized standard elements or not, promise buildings produced in a quality-controlled environment. Not only does standardization provide for efficiency in high volume of production but also coordinate design configuration and allow for customized solutions (explained later).

The consistent aspect is that correlation between efficiency of mass production, quality of prefabrication, and the variability of mass customization should be supported by flexibility in design and production processes. According to Nabeel Hamdi, "flexibility expresses freedom to choose among options or devise programs that fit individual needs and aspirations, whether for building, finance, ownership, or management [....] such designed capacity has come to influence the size and spatial configuration of built environments, services and/or the technology of building components themselves" ([5], p. 51). Beim et al. [6] refers to flexibility as a parameter to measure the quality of architectural products. A product has high quality, if it satisfies a large scope of customer expectations and preferences. Satisfying customer expectations is highly dependent on the flexibility of products that could respond to the heterogeneity of customer demands. The more flexible the product is, the more quality the product has. Thus, flexibility reflects stability and responsiveness of design and production to changing customer demands to prevent the excess of production cost while maintaining the quality of customized houses (argued later).

3 Mass Customization Space in the Housing Industry

Several efforts have been attempted to conduct fundamentals and enablers of mass customization. Achieving efficiency at or near that of mass production is dependent on various managerial and technical aspects, which can be enhanced by digital and information technologies. But there is a steady fact in each approach—the satisfaction of customer demands—which must be considered concurrently with maintaining reasonable production costs at, or nearly at, that of mass-produced products. Zipkin [7] refers to three elements from which mass customization can be realized as the capability of a system to offer individually tailored products or services on a large scale; they are elicitation, process flexibility, and logistics. While elicitation refers to the issues dealing with eliciting customer-specific information regarding product attributes, flexibility refers to strategies, means, and methods of effective and efficient design and production processes. The third element, logistics, refers to transportation tasks and post-processing stages where products are fabricated and are ready for delivery. Salvador et al. [8] identify

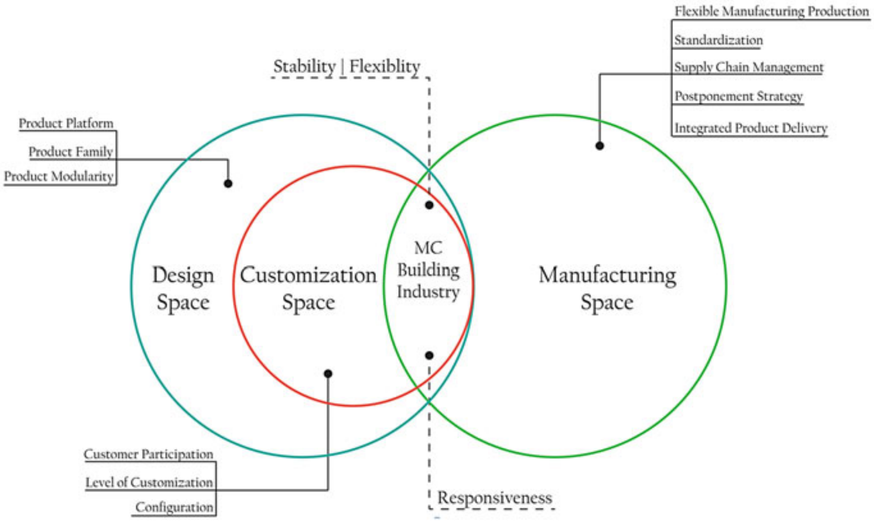

Fig. 1 Diagrammatic representation of mass customization space in the housing industry

three fundamental capabilities for successful adaptation of mass customization: first, solution space development, which refers to the design of product attributes with customer needs; second, robust process design, which refers to the ability to reuse organizational resources; and third, choice navigation, in which customers can identify their individual solutions with minimum complexity and burden of choices. Figure 1 illustrates the diagram of mass customization space in the housing industry including enablers to support design space, customization space, and manufacturing space.

3.1 Design Space

Mass customization is tightly linked to ways the product is designed. Three key elements in the design of customizable products are product platform, product family, and product modularity. First, product platform refers to a set of components, modules, or parts that are physically connected and allow the efficient development of derivative products [9, 10]. According to Robertson and Ulrich [11], "by sharing components and production processes across a platform of products, companies can develop differentiated products efficiently, increase the flexibility and responsiveness of their manufacturing processes, and take market share away from competitors that develop only one product at a time" ([11], p. 20).

Second, product family refers to a group of related products where product variations can be obtained by customizing the components of product family while maintaining the basic product platform. The concept of a product platform and product family in the building industry can be approached through industrialized building systems. For example, by dividing a building into two parts consisting of support (chassis) and infill, Habraken [12] proposes a new concept, known as Open Building (OB) to support flexibility in design and customization. This concept looks for independence between building components, which results in more freedom of change. While support (chassis) refers to a product platform that constitutes the building's structure, infill refers to the interchangeable portions of the building, such as external envelope panels and partitions. Achieving the maximum flexibility (spatial and functional) in buildings can be reached by coordinating the right set of subsystems. In this approach, a building is divided into components, known as subsystems, based on their technical characteristics [13–15]. Richard [13] divides a building into five subsystems including structure, envelopes, partitions, services, and equipment. In the Japanese home industry, for example, Toyota Home and Sekisui Home use steel frame units as an adjustable platform, and building components, which are placed on the platform, can be customized. Sekisui Home allows configuration on surface structures and painting for façade elements, while Toyota Home provides options for materials and colors of exterior surfaces.

Third, product modularity refers to organizing complex products by decomposing them into simpler portions so they can be managed independently [16]. The basic idea behind modularity is "to design, develop, and produce parts which can be combined in the maximum number of ways" ([17], p. 38). In this way, modularization reduces the complexity of product design, where product variations can be created by using the same number of components within a product family. Product modularity in the housing industry is attributed to prefabricated systems, where housing components can be practically prefabricated and delivered on-site as either modules or kit-of-parts. For example, IKEA BoKlok house comes in several different varieties which are all based on the same construction and delivery process [18].

3.2 Customization Space

The customization space is attributed to the customer taking part in design and production processes. As design tasks change, producers and customers become involved in design and production processes together; customers become co-designers. Active participation of customers modifying houses can be supported by participatory design. According to Sanoff [19], participatory design is the act of involving the customer in the design process and can be conducted in two ways: colocated or dislocated. In colocated participatory design, homebuyers and homebuilders meet in person to clarify the design requirements and discuss changes as design progresses. Instead of face-to-face communication, dislocated participatory design provides for an interface where customers are offering a limited number of options from which they could make a decision about different part of a house. This approach takes in the form of web-based customization system;

such an application by prefabricated housing companies, Resolution: 4 Architecture, LivingHomes, and Blu Homes, offers customers the possibility to navigate solutions at different levels and modify the design. In this method, there may not be sufficient amount of choice offered, and because the designs are created without customer involvement, there is no promise of customer satisfaction. Alternatively, dislocated participatory design can be pursued by a user-driven design method [20]. In this method, customers are given more flexibility to engage in the design process, to define, and to modify individual solutions. Although this method would offer more promise in achieving customer satisfaction, it has a backfire: that is, customers are not professional designers, and they may suffer from a lack of necessary knowledge and skills, which consequently may lead to invalid solution (argued later).

The effectiveness of customer participation is highly dependent on the level of customization. Building customization can be performed through changes in the building form, floor plan, as well as layouts and finishes. Hofman et al. [21] broke a building into five levels of intervention, which include interior finishes, volume and exterior, floor plan, technical systems, and environment, based on 35 housing attributes customers were offered to configure. Mishra and his colleagues [22] identify three levels of customization in the building industry, including variation, which refers to the interior "fit-ups" and building appliances; permutation, which refers to the customization of building elevations; and configuration, which refers to changes in building geometry through floor plan changes. Both variation and permutation produce customized solutions based on modular techniques. Nahmen and Bindroo [23] refer to the survey assessed by US-based industrialized homebuilders and identify four levels of customization, including no customization, minor floor plan changes, extensive floor plan changes, and total customization.

The space in which customization occurs is infinite, but the amount of customization is determined by the moment the customer enters to the production process. Duray et al. [24] develops a typology defining the relationship between the degree of customization and points of customer involvement. Based on the point of customer involvement in the production cycle, Lampel and Mintzberg [25] developed five types of mass customization based on the point of customer involvement, including pure standardization, segmented standardization, customized standardization, tailored customization, and pure customization. An earlier instance of customer involvement would result in having more flexibility in production customization. In pure standardization, customers do not enter the production process, and the only flexibility provided in that inherent in the product. In segmented standardization, the customer enters the production process in the distribution phase—for example, having control on the delivery schedule. Both tailored customization and customized standardization deal with customizing standard products, but in different levels, and they employ different methods. Tailored customization deals with customer involvement in customizing a standard product at an early stage of the design process and therefore offers the highest level of customizing standard products. The deeper the level of customization, however, the higher the complexity of design validation. Building on Lampel and Mintzberg's [25] studies, Barlow et al. [26] studied Japan's industrialized housing industry and revealed that the housing industry in Japan has achieved a relatively high degree of customer focus.

According to Barlow et al., [26], Sekisui Heim adopts a customized standardization approach where housing modules based on individual rooms are created in factories, while Sekisui House adopts tailored customization approach where standardized components and subassemblies are configured on-site.

Mass customization can be implemented in different ways. Anderson [2] identifies three ways of customizing products including adjustable, modular, and dimensional customizations. First, adjustable customization refers to the configuration of products through a reversible method where adjustments by the factories or customers make the product customized. In the building industry, adjustable customization refers to the functional and spatial flexibility in building layouts through reconfiguration of building components by incorporating different building systems. To that extent, spaces can have many uses or might change physically with moving partitions or walls that can be relocated.

Second, modular customization refers to a design of product family in which functions are designed in standard modules that can be combined differently. The most obvious form of modular-based product architecture is "Lego" or building block modularity. Ulrich [16] refers to six types of modular architecture including "component-sharing" and "cut-to-fit" with the high degree of customization to component-swapping, bus, sectional, and mix modularity, with the low degree of customization. In prefabricated modular housing, modules can be combined in three ways: (1) slot modular, where each of the interfaces between modules is of a different type than the others, so the various modules in the product cannot be interchanged; (2) bus modular, where there is a common bus to which the other modules connect via the same kind of interface; and (3) sectional modular, where all interfaces are of the same type, but there is no single element to which all other modules attach.

Third, dimensional customization (or what Ulrich [16] calls "cut-to-fit modularity") deals with tailoring products at an early stage of the design process and thus offers the highest level of customization [25]. In dimensional customization, unlike other types, components can be tailored up to physical dimensions before their fabrication and assembly stages. In this scheme, the form is easy to tailor, and any modification performed by customers will impact the entire model. The dimensional method of customization can be attributed to the scale-based configuration, where "scaling one or more variables to stretch or shrink a platform and create products whose performances vary accordingly to satisfy varieties of market niches" ([27], p. 7). In architecture, scale-based customization can be found in the work of architects responding to the needs of adaptability linked to various market niches. Friedman [28] uses scaling for wall panel specifications, permitting various interior layouts and variations on house elevations.

Customer participation and the process of configuration can be enabled by configuration toolkits [29–32]. As noted by Thomke and von Hippel [29], "outsourcing a portion of the task to customers can be an effective approach for speeding up the development of products better suited to customer needs" ([29], p. 11). There are several efforts placing emphasis on the development of computational-based design tools [33–39]. For example, Lawrence Sass [33] developed a computational-based design tool, a Palladian Design Engine, which systematically extracts the rules from Palladio's text and the construction practice of the time and codifies them into a shape grammar. Building on that work, Jose Duarte [34] developed a computational design engine that encodes the design rules of the work of the architect Alvaro Siza into a shape grammar and generates numerous housing layouts. In another example, Lauren Johnson [35] developed a rule-based system, B-Shelves, to produce mass custom furniture. B-Shelves are designed as customizable, freestanding shelving units made up of a series of interlocking boxes [35]. Through a web-based platform, the customer can create specific shelving configuration by determining the shelf size, the arrangement of boxes, and finishing options.

3.3 Manufacturing Space

The flexibility of manufacturing space reflects the capability of a system to produce custom products with efficiency at, or close to, that of mass production. Advances in design and manufacturing technologies increase the system responsiveness to make product variations with the efficiency of mass production [2, 32, 40]. As a fundamental element of industrialization, computer-integrated manufacturing (CIM) refers to the overall term for computer-integrated production and can be divided into computer-aided design (CAD) and computer-aided manufacturing (CAM). Paired with CAD/CAM technologies, computer numerical control (CNC) and flexible production automation (FPA) systems enable custom products to be manufactured with an efficiency close to that of standard production [41]. Taking advantage of file-to-factory processes, geometric information of digitally driven products could be parametrically extracted and transferred directly into computer numerical (CN) manufacturing machines. Innovations supporting computer-aided manufacturing technologies in the building industry can be divided into mechanical tools, automated tools, and intelligent tools [42]. They hold values for efficiency in production by substituting labors with machines. While mechanization is brought up whenever machinery is employed to ease the work of the labor, automation refers to manufacturing tools that operate processes repeatedly and continuously [42]. Pairing automation with numerical control (NC) systems offers the potential to produce custom products while still realizing the efficiency of prefabricated, mass-produced products. Robots are intelligent and multifunctional tools that could support mass customization. As noted by Roger Richard, robots are programmed "[...] to perform diversified tasks with multi-axis flexibility" ([42], p. 18). The application of robots in architecture has been widely studied, and researchers refer to their potential benefits in manufacturing, assembly, and construction as well as their precision, speed, versatility, and multifunctionality [43]. In Japanese housing industry, for example, Daiwa is a fully automated home factory that uses robotics along with manpower to prefabricate a complete house within 5 h ([4], p. 54).

In another fundamental element of manufacturing space, standardization refers to producing standard components, which can be configured (modified or combined differently) to produce custom products. According to Salvador et al. [44], "standardization is important because the interactions and interdependencies among different component families depend on the desired final product configuration" ([44], p. 68). In the building industry, manufacturing of family components needs to be standardized in a way that their configurations are limited by design (or manufacturing) constraints. Incorporating standard family components could leverage manufacturing efficiency and reduce the total cost of the customized products [41]. In the prefabricated housing industry, decisions about which components standardize, and which vary within a product family, are interrelated and require a crucial understanding about design requirements and manufacturing considerations.

Supply chain management is concerned with the organizational management issues such as where components should be produced from, where they should be assembled, how to minimize the assembly costs, cost-effective ways of distributing products that are manufactured in high volume, and other questions. It has been argued that companies that try to adapt mass customization typically deal with the lack of flexibility and responsiveness in the supply chain process [45]. The integrated project delivery (IPD) process is a supply chain strategy that collaboratively integrates product development teams. According to the American Institute of Architects (AIA), IPD is defined as "a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" ([46], p. 2). The core of IPD is to enhance collaboration between project team members including the owner (or customer), designer (or engineer), and constructor (or manufacturer), through early collaboration in the product development process. IPD provides benefit for "improving the team's ability to control costs and manage the budget, all of which increase the likelihood that project goals, including schedule, life cycle costs, quality and sustainability, will be achieved" ([46], p. 3). The integrated delivery process can be enabled by digital and information technologies. As a design methodology, BIM has "the ability to digitally coordinate the often complex process of building prior to actual construction" ([47], p. 14). While flexible manufacturing production removes distinction between design and production, building information modeling (BIM) provides a platform for integrated processes built on coordinated reliable information exchange among team members.

Finally, postponement, or decoupling, means that due to the uncertainty of mass customization demands, a company delays design, production, or assembly until customer orders have been received [48]. This way, a company can fine-tune products through the different stages of design, production, development, and distribution. Employing postponement strategy has potential benefits of reducing the cost of inventory, reducing the planning complexity, and saving capacity utilization and stability while avoiding lost sales [49]. For example, Toyota Home keeps inventory low by linking directly to customer order [50]. The customizable options are produced based on the same raw materials that are kept in the stock, so when an order is issued, they can pull off the shelves, create modules, assemble them, and erect them on the site [50].

4 Challenges

The adaptation of mass customization is a multidimensional challenge. From a customer's perspective, there are always challenges and risks associated with the co-design activity: that is, customers may not have sufficient knowledge and skills to perform the configuration task. In the co-design activity, the customer is an end-user who directly interacts with the toolkit, enters information, and designs (or customizes) products. In that fashion, the utilization of toolkits could be a major driver of cost, complexity, risk, and extra effort [30, 51]. This argument raises an issue for research that focus on the design of configuration toolkits. For example, Von Hippel [30] refers to user-friendliness of configuration toolkits supporting user-specific design language—that is, toolkits should demand for less skills and efforts to work with. Higher simplicity, however, might limit a customer's freedom in design and individualization.

The complexity of co-design activity is also attributed to knowledge about product architecture and expertise in customizable attributes. Researchers place emphasis on the fact that knowledgeable customers are generally less averse to choose complexity and more interested in customizable offers. For example, customers who already have bought houses would find it easier to choose the most desirable layouts or materials than those who never have bought a house. In an experimental study, Dellaert and Stremersch [51] examine the customer interaction with a design toolkit for personal computers. They investigated consumers' expertise and evaluations of different mass customization configurations on product utility and perceived complexity, which in turn both influence mass customization utility. The results show that expertise lowers the negative influence of complexity, as "consumers with high levels of product expertise consider mass customization configurations less complex that do consumers with low levels of product expertise, and that for more-expert consumers, complexity has a less negative impact on product utility" ([51], p. 129). It has also been argued that customers who became more accustomed with the product could better make rational comparison between choices, and those with good product knowledge could better grasp product functionalities and reduce the solution space to a manageable subset from which they make optimal choice [51].

From a company's perspective, it is yet to answer to what extent the flexibility of housing customization can provide for efficiency of the housing production process. Difficulties in adapting mass customization in the housing industry, as noted by Kieran and Timberlake [52], are due to three issues: first, there are few overlaps between design, manufacturing, and construction; second, fragmentation of building industry as thousands of small companies are involved in design and production processes; and third, the need for embracing new technologies and methods of manufacturing. It can also be argued that customer participation brings the challenge of design validity—ensuring that individualized solutions are viable. Homebuilders prefer to limit customer participation at the level of choice selection and often offer filtered information about housing options. The deeper the level of customization, the higher the complexity of design validation. Allowing the customer to intervene at an early stage of the design process, especially in housing, makes it difficult for the designer to ensure design validation. If the proposed solution does not meet customer satisfaction (as it may not necessarily do), the entire customization process needs to start over. The process of manually evaluating and adjusting changes against constraints is error-prone, costly, and time-consuming. Automated constraint checking of individualized housing could significantly benefit the process of design validation in that the entire model automatically updates to accommodate changes. As noted by Khalili-Araghi and Kolarevic [53], companies could benefit from constraint-based parametric modeling, where customization is performed over a single model that allows customers to explore a vast number of solutions while simultaneously complying with design rules. This helps to avoid design evaluation rework and to ensure that modification does not invalidate design intentions [53].

Furthermore, advances in digital and manufacturing technologies bring the challenges of design liability and ownership. As noted by Kolarevic [54], there are no technological obstacles to drive the design and manufacturing of customized products, but challenges are largely cultural. As argued at the beginning, mass customization requires essential collaboration between customers, designers, and manufacturers, and they need to be aware of digitally driven customized houses. Integrating advanced digital design and manufacturing technologies could provide for product optimization, coordination, and increased adaptability to design changes. However, opponents believe that this change in the design process is subject to the challenges of design liability and ownership—that is, designers and manufacturers would have to take the risk of responsibility in digitally driven products [55–57]. Furthermore, dealing with the co-design activity raises the challenge of customer responsibility in the design process. It is unlikely that customers would be willing to take responsibility for the changes applied in their houses [54].

Finally, mass customization is a customer-centric design process, and achieving the potential benefits of technological development requires a gradual transition in the cultural mindset of the company. Companies need to alter their perceptions about customers and adjust their cultural guidelines toward the profitability of customer involvement in design and production processes.

5 Conclusion and Future Research

This paper describes a comprehensive knowledge in research aiming at devising mass customization in the housing industry. It explores fundamentals and technological enablers that could support flexibility in design, customization, and manufacturing spaces. As argued, flexibility in mass customization offers promises in variability without sacrificing the efficiency of mass-produced houses. The suggested approach aims to bridge the gap between the customer, the designer, and the manufacturer to produce highly customized products. Through the co-design activity, homebuyers could have a greater influence on the overall design of their homes. This could offer a promise of homebuyers finding satisfactory solutions and homebuilders to achieve more profitability. The challenge remaining is yet to answer social, cultural, and regulatory issues affecting the acceptance of such an approach by both homebuilders and homebuyers.

Future research could be dedicated to developing configuration toolkits based on technological advances (design and manufacturing) that could support effective customer participation in the design process. Truly achieving customer satisfaction requires highly customized houses that are tailored as one-of-a-kind products. Dimensional customization, as a suitable paradigm for the housing industry, allows customers to participate at an early stage of the design process so that a building geometry can be tailored individually using dimensional parameters. The realization of such a technology should be effectively examined in the real context to understand that to what extent the flexibility of customization space (variability of customized solutions) can be limited by the challenges laid behind the validity of customized solutions. It is essential to examine the challenges and difficulties that could hinder homebuyers and homebuilders to embrace new technologies in their design and production processes.

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Product and Service Variety Versus Internal Performance: Toward New Balances

Khaled Medini, Abderrahmane Moujahid, Xavier Boucher, and Alain Bernard

Abstract Increasing customer demands for individualized solutions has a major impact on the manufacturing sector. Companies are confronted to producing high volumes in order to meet market demand while customizing their offering to meet specific customers' requirements. One of the subsequent major challenges of this situation is to cope with the high offering variety while ensuring higher performance within the production system and supply chain of the solution provider. This paper deals with the impact of integrating products and services on the variety-induced complexity. Based on a consistent literature review, a model is proposed to conceptualize the main drivers of variety management of product and service offering. The ultimate objective of the model is to support decision-makers in the identification of balances between customer satisfaction and supply chain performance.

Keywords Variety management · Product · Service · Performance · Flexibility

1 Introduction

Manufacturing companies operate in an evolving social context, shaped by increasingly diversified customer demand, awareness of the environmental impact of the manufacturing industry, competition at the national and international levels, and technological development particularly in terms of digital technologies. Taking into account all these factors requires a progressive transition of the manufacturing companies to a new model integrating customization, flexibility, and environmental concerns. The contribution reported in the paper is a part of a research project whose

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ambition is to provide decision-makers with tools for managing such a transition by focusing on the problem of managing the variety, resulting from customizing products and services, along with its impact on flexibility of the supply chain as well as its environmental impact. This paper deals specifically with the impact of integrating products and services on the variety-induced complexity. The paper extends the scope of variety impact analysis to customer satisfaction and additional value generated for both the customer and the supply chain, out of increasing offering variety. A model is proposed to identify the equilibrium between customer stratification and supply chain flexibility. A case study based on fictitious company in the hardware business is used to illustrate first findings of this research. In particular, new equilibrium is required in order to ensure flexibility and customer satisfaction when delivering products and services.

The remainder of the paper is organized as follows: Section 2 presents the research methodology and the literature review. Section 3 reports on a reference model for variety management. Key challenges for products and service variety management are discussed in Sect. 4 based on an illustrative example. Concluding remarks are reported on in Sect. 5.

2 Literature Review

2.1 Research Methodology

The literature review is organized into two steps with two complementary objectives. These steps are detailed, respectively, in the next sections. First step consists in defining and analyzing the addressed key concepts and their interactions in order to define the scope of the research topic. Second step consists of a systematic literature review to explore to which extent the research topic has been addressed by the literature. Main searched data bases include ScienceDirect, GoogleScholar, and Springer, using combinations of the following keywords: *product variety*, *service variety*, *mass customization*, *performance indicators*, *customer satisfaction measurement*, *customer order decoupling point*, and *flexibility*. The initial research resulted in 120 papers. A first two-phase screening of the articles was carried out based on their titles and abstracts, respectively. This screening has driven the number of articles down to 60.

2.2 Conceptual Framework

The main idea of the current research work is to study the equilibrium between variety of products and services and performance of the supply chain notably in terms of flexibility, in the context of mass customization (MC). In the following sections, performance refers to cost and lead time reduction and flexibility.

2.2.1 MC Rationale and Capabilities

MC can be defined as means to meet individualized customers' demands with near mass production efficiency [1]. In this sense, MC can be seen as a trade-off between mass production and pure personalization [2]. This means that standardization and commonality are still in the heart of MC although its focus is shifted to the customer. In fact, the success of MC implementation is closely related to customer involvement in the design and configuration of the offering and its willingness to pay extra costs induced by the customization [3–6]. Salvador et al. [7] identified a set of MC drivers and classified them into the three categories, so-called MC capabilities: solution space development, robust process design, and choice navigation. First capability is concerned with the identification of product attributes which translates customers' needs. Second capability refers to configuration of the supply chain resources so as to meet diversified customer demands. Third capability consists in providing support to the customer in identifying their choices [7]. From a practical point of view, coping with MC challenges requires effective management of the variety of products and services.

2.2.2 External and Internal Varieties

In order to understand variety, many authors distinguished external and internal varieties. External variety refers to the offering level of variety which is perceived by the customer. More specifically, product variety refers to the number of product variants aimed at meeting various customer needs [8].

Service variety is defined as the number of service options included in the offering [9]. Service variety management is typically based upon service engineering and modeling methods [10]. Sievanen [11] categorizes services into *back office* which refer to standard services realized without interaction with the customer and *front office* which characterize customizable services generally included in the delivery system. Back office services can be approached by the "push-flow" part of a product supply chain, while front office services are similar to the "pull-flow" part.

Internal variety is a result of the external variety and refers to the variety of the components, modules, products, processes, resources, etc. [12]. Such variety leads usually to increased complexity within the production system and the whole supply chain [13].

Meeting individualized customer demands requires a personalized offer relying on a wide range of products and services (i.e., external variety). Such a personalized offer is likely to increase both customer satisfaction which reflects the gap between customer requirements and what is actually achieved and internal variety which impacts on the performance, which impacts in turn on customer satisfaction; see Fig. 1. In this regard, the challenge of variety management is how to cope with external variety while mitigating the internal complexity and ensure satisfactory performance in terms of flexibility, responsiveness, and cost. An effective variety management allows for achieving economies of scope, through generating high variety based on a limited number of references, and economies of scale by

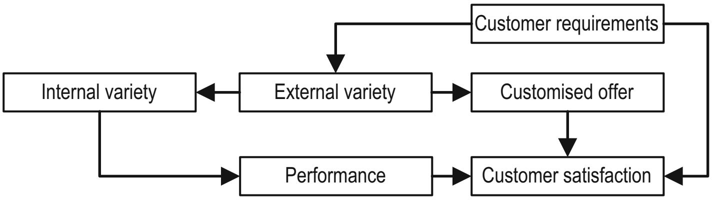

Fig. 1 Conceptual framework

inheriting mass customization standardization and commonality principles. Modularity, commonality, and postponement are among the main drivers to realize these economies through more flexible supply chains.

2.2.3 Standardization and Flexibility Oxymoron

Flexibility is among the key drivers for managing variety. It refers to the capacity of the supply chain to deal with customer demand changes through an effective management of its resources. As such flexibility leads to reducing costs and lead times and coping with individualized demands [14]. In a mass customization context, the supply chain management is ruled by a combination between flexibility and standardization. The frontier between these two management policies is defined by the so-called customer order decoupling point which refers to the point where customer order will be integrated within the supply chain [15]. The supply chain operations upstream the decoupling point are concerned with standardization and are characterized by a push-flow system. The operations located downstream the decoupling point are focused on customization and are characterized by a pull-flow system. Flexibility of the downstream operations is very important to improve responsiveness and costs. Identifying the decoupling point position goes hand in hand with the customization level (customer co-design, customization during the delivery, etc.). For a given customization level, moving the decoupling point downstream the supply chain is generally privileged in order to drive down lead times and costs. This principle is in the heart of the postponement philosophy [5, 15]. However, the need for flexibility suggests that decoupling point be moved upstream the supply chain [16]. Thus, the location of decoupling point involves a very impacting decision in managing the supply chain operations.

2.2.4 Modularity and Commonality

Coupling push-flow and pull-flow systems relies on several drivers at both the product and process levels, including modularity and commonality. Modularity contributes toward mitigating the impact of product variety on internal variety as it helps generating high variety with a relatively limited number of components through combinations [6, 17, 18]. While product modularity is based on components

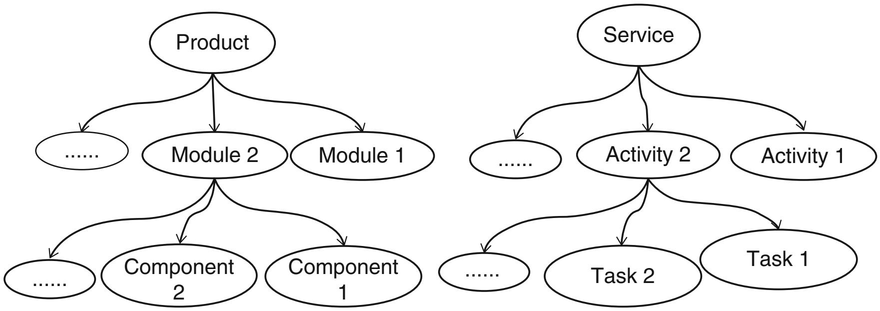

Fig. 2 Product modularity vs. service modularity

interfacing and functional dependency, service modularity is driven by activities to realize the service [11]. The question to be dealt with in service modularization is to which extend it is possible to generate service options with a limited number of activities (see Fig. 2). Song et al. [19] discussed a service modularization method inspired by traditional product modularization techniques and using service blueprinting.

Limiting the number of different components and modules in the end products and services relies also on the commonality principle [20]. That is to use same resource(s) to generate as many as possible variants (of a product and/or a service) in the offering. These resources include components, modules, activities, tools, operators, etc.

2.2.5 Customer Satisfaction

A large body of the literature witnesses the positive impact of customizing the offering on customer satisfaction. This idea is mainly supported by empirical evidences which are based on customers' feedback [21, 22]. Blecker and Abdelkafi [12] argued that customer satisfaction is impacted by delivery speed, selling price, and variety level of the offering. The identification of equilibrium between these factors is closely related to the decoupling point location. Main indicators reported on in literature for measuring customer satisfaction include rate of satisfied customers, lost customers, return rate, claims rate, growth rate of customers basis, reorder frequency, total sales volumes, etc. [23, 24].

2.3 Systematic Literature Review

The objective of this section is to explore the research works addressing the concepts discussed above and their interrelationships. To this end, several keywords combinations have been used as shown in Table 1.

Table 1 Combinations of the keywords

Combination	Keywords			
	Product variety	Service variety	MC*	PI**
C01 – Pr.Se.Mc.Per.	X	X	X	X
C02 – Se.Mc.Per.		X	X	X
C03 – Pr.Mc.Per.	X		X	X
C04 – Pr.Se.Mc.	X	X	X	
C05 – Pr.Se.	X	X		
C06 – Se.Mc.		X	X	
C07 – Pr.Mc.	X		X	
C08 – Mc.Per.			X	X
C09 – Se.		X		
C10 – Pr.Per.	X			X

*Mass customization
**Performance indicators

Table 2 Distribution of addressed topics among analyzed articles

	%	Examples of references
C03	37	[8, 12, 25–31]
C02	13	[11, 32–37]
C06	10	[38–41]
C10	8	[2, 18, 42, 43]
C07	8	[44–46]
C01	7	[18, 20]
C08	7	[47, 48]
C04	5	[49]
C09	3	[19, 50]
C05	2	[51]

After a two-step screening, the articles were categorized according to the keywords combinations before being analyzed. Table 2 shows the distribution of addressed topics among analyzed articles. The topics are sorted by their respective shares in the analyzed articles (third column).

In general, it can be noticed that the topics are unequally addressed in literature. Unsurprisingly, C03 resulted in the highest number of relevant papers (almost 40%). This witnesses that, in the literature, the focus of MC has been generally put on products rather than service. Looking at C02 and C06 shares in the articles, one can see that service started to emerge in the MC context during the last decade. There is even an exclusive focus on service in the MC context in more recent research works (see Fig. 3). C07 and C10 show that the body of literature addressing product variety is relatively significant. The research works addressing both products, service variety in an MC context, are still scarce (cf. C04, C05, and C01).

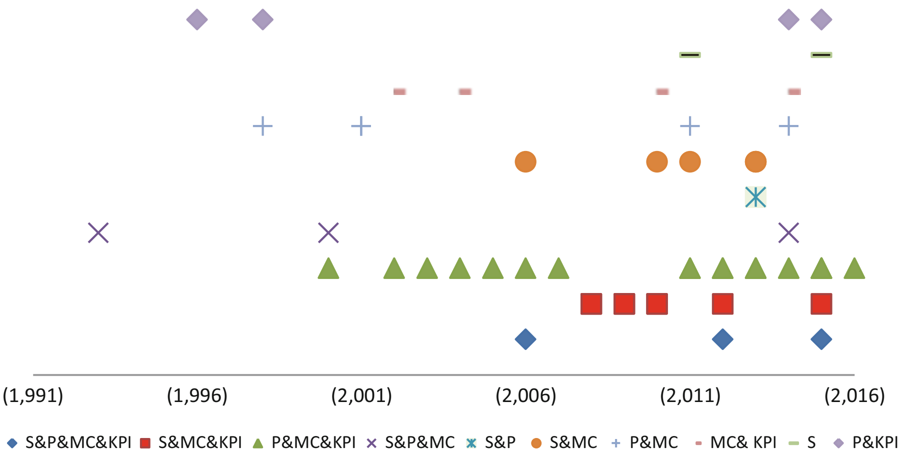

Fig. 3 Distribution of the addressed topics over last decades

3 A Reference Model for Variety Management

The rationale of the reference model is to provide an overview of the drivers for managing product and service variety at strategic and operational levels. In this sense, the next two subsections point out key capabilities for products and services mass customization and variety management drivers, respectively. The drivers identified in Sect. 3.2 extend the key capabilities defined in Sect. 3.1.

3.1 Products and Services Mass Customization (PSMC) Capabilities

The definition of product and services customization capabilities is inspired by the MC capabilities model from Salvador et al. [7]. The new capabilities (proposed ones) extend the scope of the traditional model by including services as a part of the MC offering and the required processes to realize and deliver such services. In this sense all three capabilities will evolve to fit into the new product and service perspective. Starting from [7] the PSMC capabilities can be defined as follows (see Fig. 4).

- *Solution space development*: this capability is concerned with the identification of product and service personalization attributes, which allow meeting specific customers' needs. These needs are either objective, i.e., associated with fictive and objective customers, or subjective, i.e., referring to real individual needs translated in customer order [7, 12, 23, 24].

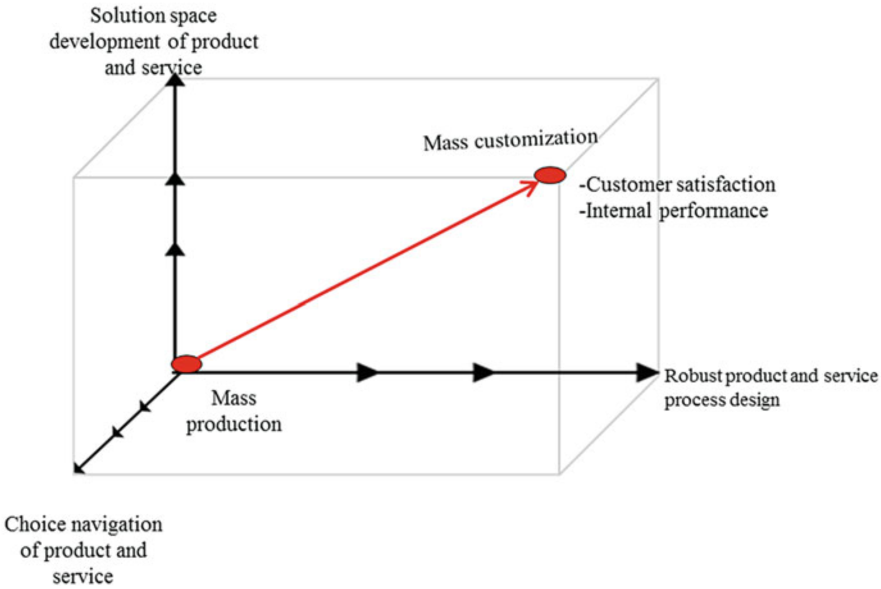

Fig. 4 PSMC capabilities

- *Robust process design:* this capability refers to the reuse and combination of organizational and value chain resources to fulfill differentiated customers' needs in terms of products and resources. In other terms, the aim is to design flexible processes supporting offering variety management [6, 7, 12, 13, 17, 18, 20].
- *Choice navigation:* this capability is concerned with supporting customers identifying most suitable products and services to customer needs while reducing the complexity and burdening customer choice [7, 12].

3.2 Variety Management Drivers

The identification of product and service variety management drivers is based on the model introduced by Blecker et al. [12] and on the PSMC capabilities described in the previous section. Blecker et al. [12] identified and analyzed the interactions between several drivers impacting variety management, using an influence diagram. Their model is however focused on physical products. The current research work extends this model by introducing service-related drivers and by linking them to the strategic capabilities.

The PSMC capabilities are translated into following drivers and interactions (Fig. 5). In Fig. 5 solution space development, robust process design, and choice navigation are highlighted with yellow, light red, and light blue, respectively. The hexagon shapes refer to the main objectives and the boxes to the drivers and metrics.

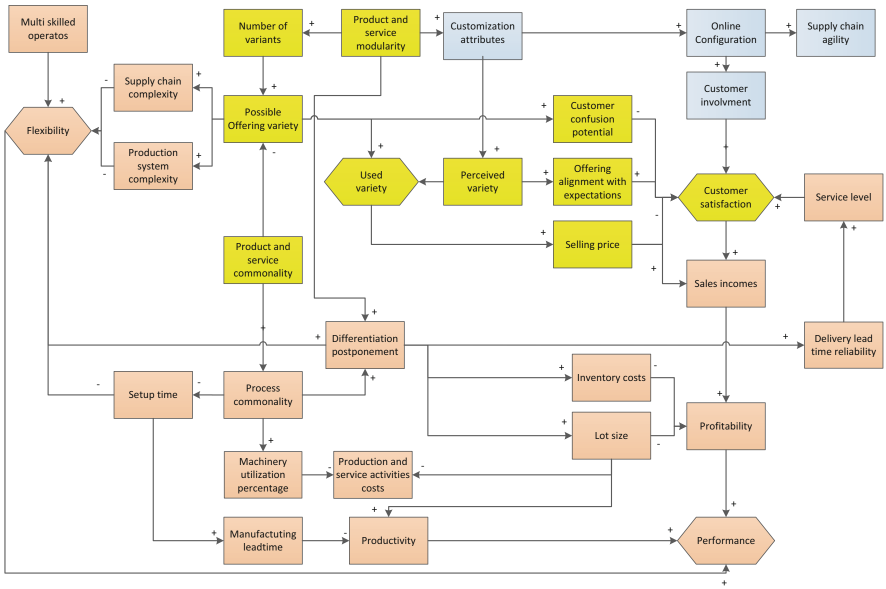

Fig. 5 Variety management drivers

Solution space development is driven by the definition of possible variety of the offering. Obviously, possible variety is positively impacted by the number of product and service variants. In contrast, product and service commonality impacts negatively on possible variety although it contributes to the economies of scale. The number of product and service variants is correlated with the modularity level of product and service, respectively.

Robust process design is driven by flexibility, performance, and agility. Flexibility is improved through postponement of products and services differentiation. The postponement is driven by modularity and commonality. Additionally multiskilled operators contribute toward higher flexibility. The process commonality which is positively impacted by product and service commonality implies lower setup times, which reinforces the flexibility. The flexibility is however negatively impacted by production systems and supply chain complexity, induced by the number of product and service variants. The performance is closely related to the productivity, profitability, and flexibility. The productivity is impacted by the lot size and the lead time, which is turn, positively correlated with the setup time. The profitability is obviously inversely correlated with inventory costs and lot size. Sales income contributes however to increasing the profitability. Inventory costs are positively correlated with postponement level. Production and service activities costs are impacted by the lot size and machinery utilization percentage. Supply chain agility is positively impacted by the use of web configurators through the acquired experience out of customers' use of the configurators.

Choice navigation relies on effective accompaniment of customers in identifying their choices through web configurators (e.g., ease of configuration, number of available options, pricing, etc.), thus enhancing their involvement in the value creation process. The configurators' success depends on the effectiveness of the definition of customization attributes.

Customer satisfaction depends on the service level, alignment of the offering with his expectations, confusion potential, and the selling price. The service level reflects the quality of the realized service for the customer. It includes but is not limited to the delivery time reliability which is, in turn, impacted by the postponement level. Customer confusion potential is inversely correlated with the possible offering variety. Possible offering variety refers to the solution space of the available offering alternatives (product and service variants combination). Possible offering variety is positively correlated with used variety. This latter measures the rate of frequently ordered variants of product and services from the possible offering variety. Offering alignment with customer expectations depends on a variety of factors including customization attributes and their impact on the perceived variety by the customer. Possible offering variety may lead to customer confusion which is likely to drive down customer satisfaction. In contrast, customer satisfaction is likely to increase sales income.

Variety management efficacy depends on the equilibrium between customer satisfaction and internal performance. Flexibility and agility are two key principles for achieving this equilibrium. To operationalize these principles, several drivers span over the three PSMC capabilities and contribute to such equilibrium.

4 Discussion and Research Perspectives

The paper reports on an initial conceptualization of a variety management model based on previous research works in the literature. The integration of the service variety considerations within the model is consistent with the recent literature promoting the shift from mere products to global solutions based on combinations of products and services. As such, the framework provides clues for managing the variety of the offering (product and/or services) while considering both customer satisfaction and internal performance.

The model spans over managerial and operational perspectives through mapping the three mass customization capabilities [7] to the model developed by Blecker et al. [12]. This reinforces the applicability of the proposed framework by practitioners.

However, so far only some of the relevant drivers have been considered. The model needs to be evidenced through case studies which are likely to extend it further.

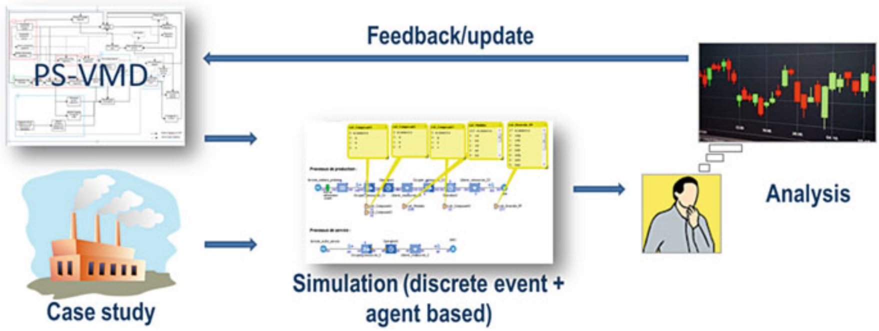

Fig. 6 Validation process

Beyond contributing to the improvement of the understanding of variety management of product and services, the model provides support to decision-makers in selecting the right drivers and thus defining proper policies for maximizing both customer value (satisfaction) and company value (performance) out of a given product and service offering.

Since the model is still in its infancy, its suggested use scenario is coupled with the validation process (see Fig. 6) [52, 53]. In other words, the use is expected to contribute to the progressive validation of the model. Currently, a simulation model is under development and is used for testing the impact of the drivers on some aspects of the company performance and customer satisfaction. Coupling the simulation model with case studies allows to get feedback on the assumptions made in the model and thus refining or validating them.

5 Conclusion

Based on a systematic literature review, the current paper evidences the lack of adapted decision supporting tools for managing the variety of product and service. Subsequently, a first conceptualization of a variety management model is provided based on previous research works in the mass customization domain. The originality of the proposal lies in (i) integrating the service dimension in the offering which is not limited to the mere physical product anymore and (ii) the extension of the management drivers to include key elements such as flexibility, agility and performance, and customer satisfaction. This supports the identification of trade-offs between customer and company values in a given offering.

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Validation of Metrics for Mass Customization: A Pre-study of Validation Methods

Kjeld Nielsen, Thomas Ditlev Brunoe, and Simeon Dechev Simeonov

Abstract Over the last two decades, literature presents mass customization metrics; recent research presents these in relation to another recent research: the framework of three fundamental capabilities in mass customization. The metrics presented are all considered useful in company applications like ERP systems. A firm validation of each metrics is not confirmed in the literature. This research aims to address the lack of method for validation: firstly, by identifying a commonly accepted method or procedure to follow to validate a metric (case study was identified as such commonly accepted method) and, secondly, by performing a simple analysis following the method proposed to assess the potential (an analysis of repurchase rate metric was performed on a small case dataset, and it clarified the potential in the procedure for validation).

Keywords Mass customization · Metrics · Validation

1 Introduction

The recent research presents and introduces metrics for assessment of mass customization [1–5]. The recent research had the objective of establishing a framework, making practitioners, researchers, and others able to assess and measure mass customization progress, assessment, and measurement in a company or across companies as benchmark tools. The paradigm for the work was primarily established based on the work “Cracking the Code of Mass Customization” [6]. Herein the authors define the fundamental capabilities needed for mass customizers as solution space development, robust process design, and choice navigation, which were the basics used as framework to establish the knowledge about metrics useful for assessment of mass customization. The framework and the metrics can be

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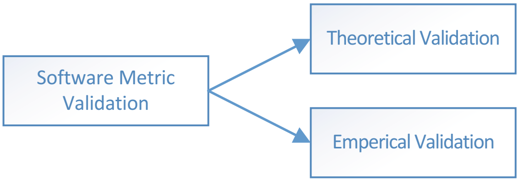

Fig. 1 Model of the software metric validation. (Adapted from Srinivasan and Devi [10])

useful on both short- and long-term development. As part of the research, the literature review identified some metrics and other new metrics were presented in the abovementioned work; in total 35 metrics have been presented as relevant for assessment and measurement of mass customization in addressing the three fundamental capabilities. In the framework, it was initially established that data to calculate the metrics generally should be easy to access in ERP systems and no extra effort or data collection should be necessary; this should make it easier to establish some knowledge of how well a company is doing a mass customizer or benchmark across companies. Part of the work categorized the metrics in relation to the three capabilities [1] as shown in Fig. 1.

During the work of establishing the framework and the metrics limited resources left a gap of validating and verifying the metrics in relation to definition, categorizing, and measure. The objective of this research is to close that gap, and the aim of this paper is to present the first part of that research. Most has to be done before a full validation and verifying of all metrics has been performed, and the intention is to address this along when other research in the specific field are performed. The first part of that task is to establish knowledge about validation tools and validation procedures, which frames the objectives and research question in this paper:

How can mass customization metrics be validated?

2 Research Approach

The research approach is done first with a basic literature review to establish knowledge about "validation of metrics" from where a method and tools for validation are chosen as best candidates for the validation process, and finally a few metrics have been selected and validated through some data collected from case companies.

2.1 Validation Methods

A literature search for "validation of metrics" soon indicates that formal qualification of metrics is a discipline done mostly in software domain. Going deeper into the literature, it is also indicated that several models and tools to "validate metrics" have been established over time; most work address models and include often specific criteria to be included in the validation procedure. A specific research has reviewed the literature and found 47 criteria to constitute a validation of a specific software metric [8]. Another research introduces a ladder with four validation criteria before the metric is validated [9]. Among a number of research introducing criteria and procedures, the model introduced by Srinivasan and Devi [10] was found as a good candidate for this research validation.

K.P. Srinivasan and T. Devi [10] investigated the different methodologies that are familiar to software engineers when it comes about metric validation. The writers, who are also metrics developers themselves, are carrying out a vast research on relevant literature about software metrics validation. After proposing a set of six result-based software metrics for measuring object-oriented design quality effectiveness, the authors go further and introduce a contemporary type of metrics that assess software coding. The paper is based on researches that had contributed about the validation process in terms of metric validity, it is claimed that in the past most important events of metric validation shows that a lot metrics had been proposed and then validated by renowned developers from software engineering.

In relation to "our" metrics, this methodology will be applied in a limited version. First of all the authors are referring to a general conception that software metrics has to be validated "theoretically" as well as "empirically" as seen in Fig. 1.

According to Srinivasan and Devi [10], the theoretical validation confirms that the measurement does not violate any necessary properties of the elements of measurement; hence a validating process must ensure that the metric itself does not influence the data environment and dataset it comes from, when performing used as a metric in system. This process confirms validity or invalidity of the metric [10].

Empirical validation is done in one or more of the three options: (1) experiment, (2) case study, or (3) survey, as seen in Fig. 2. The authors refer to other research and argue that these are well known and commonly used, hence an evidence that this approach of validating metrics would work.

When introducing a new metric through academic work empirically, evidence is often lacking in the study, which has been addressed by Sanjay Misra [11]. It is here argued that for proper empirical validation, one must study the new metric with real data from the industry. The author states his grounds and argues that a metric should be validated through the use of company data or actual case that involves a real firm with real problems. After an exhaustive survey of literature

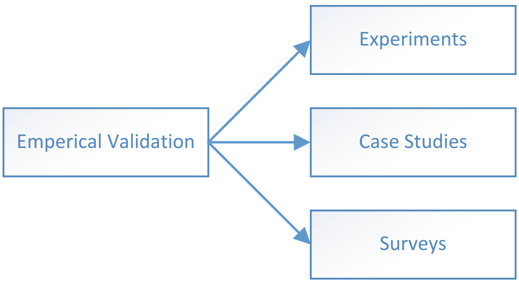

Fig. 2 Proposed procedures for empirical validation of metrics. (Adapted from Srinivasan and Devi [10])

for software metric validation, Sanjay Misra [11] reviews what are the different empirical approaches to acquire validity of a software measurement. These methods are the same as the previous two authors proposed – experiment, survey, and case study. It is argued that there are a lot of cases when researchers conduct small case studies without the use of real data, which makes them unreliable for proving validity, and conducting such case studies is leaving gaps and the results are still open for discussion [11]. The authors further argues that the case study perform a crucial part when it comes to validation of newly proposed metrics. The efficiency of a contemporary measurement when proven with data from a real source. After proved with a case study, a metric is proposed to be used in industry or real company cases. It can be considered that the case study is a mandatory preceding step, before using a metric in real company matter.

The concept of this approach is straightforward for researchers, yet not a trivial task. Experiments can be carried out in laboratories where a control research could be made, and then the result can be used to analyze if the metric is measuring the concept correctly or not. Other experiments involving the industry or workplaces where a study can be established with the use of company data. Hence based on the review of literature, it is argued that validation based on case studies would validate the proposed metrics for mass customization.

2.2 Case Study Design

The objective of this research is to establish a standard procedure to validate proposed mass customization metrics presented in other research. Hence, this research will be limited to three metrics, which are analyses in datasets from two companies. The three metrics are as follows.

Customer repurchase rate is a metric that present knowledge about both choice navigation and solution space development [3, 7, 12].

$$\mathrm{RR} = \frac{\text{number of repurchases}}{\text{total number of purchases}} \tag{1}$$

Source: Piller, 2002 [13]

This metric describes how often is a product repurchased. Assessment in Choice Navigation, a low value apply information that the company provides certain solution space; it is configurable, but potential lack of customers demand. This can further indicate options that a company provides, but there is no demand on the market for them. Estimating this can help the company identify excess product variants. This will yield the benefit of lower production and storage costs. In assessing solution space development, a higher value of the customer repurchase rate indicates that the customers are satisfied with the solution space. Repurchase argues that a client is being contented with his needs. If a product is purchased by a customer more than once, it clearly shows that customer's needs are being fulfilled.

3 Results and Findings

For the analyses, data from a case company has been involved. The dataset involved has been collected through other research and are based on data retrieved from configuration systems and correlating bills of materials from the case company ERP systems.

An analysis of sales statistics identifies how many times a client returns to buy the company's products (Fig. 3). In the dataset, 20 customers are registered.

Figure 4 represents how many times a specific customer purchased a specific product. Each purchase of an item that is done more than once is considered a repurchase. Based on the specific dataset, the most repurchasing customer is the same as most purchasing customer as shown in Fig. 3. In Fig. 4 the number of customers declined to 16. The number of customers was expected to decrease because of the three individuals that had bought only one item. It is considered that the customers that do not fall in the category of repurchase had purchased a different product in all of their purchases. Hence, repurchase rate metric is validated.

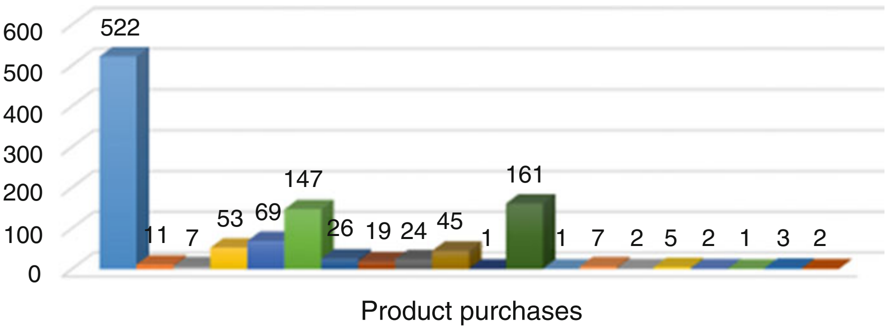

Fig. 3 Number of product purchased by customer – each color represents a specific customer

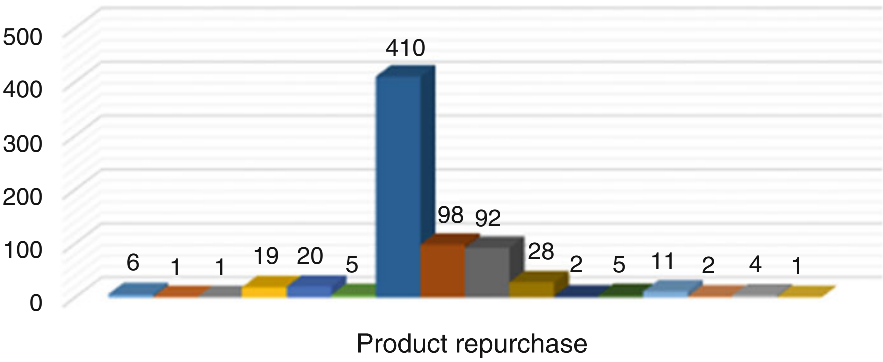

Fig. 4 Product repurchase per costumer

4 Conclusion

Establishing a framework or procedures to validate metrics for mass customization in case studies was initially clarified through a literature review. Software metric validation has in history of research been addressed, mainly to ensure quality, reliability, and consistency in software systems, often argued on because results from software systems are used in following sequences of decision-making at management level. The same objectives are expected to rule for mass customization measurement and assessment metrics, because these are look-a-like of nature as software metrics, furthermore the are expected to be implemented in decisions systems like BI applications. Case studies are well-documented approach for such validation and, hence, in this research appointed as the best alternative of the proposed in the literature. In the research a small case-based dataset was introduced and repurchase rate metric was selected for a closer analysis. The result of this analysis indicates it is possible to extract the data from a case-based dataset needed for the metrics, and furthermore, it indicates that it is possible to use the result of the metric calculation as indicated in the previous research on mass customization metrics.

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Teaching Solution Space Development: Experiences from the Hanover Knowledge-Based-Design-Lab

Paul Christoph Gembarski and Roland Lachmayer

Abstract Although the concept of knowledge-based design (KBD) and engineering (KBE) is discussed for more than 20 years, only little application outside of academia is documented. Existing approaches are predominantly limited to niche design activities or to aviation and automotive engineering. This fact does not originate from missing IT support or the lack of KBD functionalities in contemporary computer-aided design (CAD) systems but rather from deficiencies in education. As a study showed, in many curricula in engineering design the setup, structured exploration and management of (geometry-based) design solution spaces for configuration and optimization are yet not present. In the following article, we present our experience with the Knowledge-Based-Design-Lab which is held at the Leibniz University of Hanover for 5 years. Scope of the tutorial is shifting the traditional modeling of mostly rigid geometrical product models to automate routine design tasks and create configurable virtual prototypes.

Keywords Solution space development · CAD configuration · Project-based learning

1 Introduction

For about 20 years, the use of computer-aided design (CAD) and engineering (CAE) tools has contributed to a steady increase in competitiveness and innovation capability of many companies in engineering. Especially the use of parametric design systems offers great potentials regarding adaptive and variant design activities [1]. In particular the possibility to define mathematical, geometrical, and logical

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constraints between parameters in a CAD system allows the implementation of explicit knowledge in digital prototypes. Here, the designer also defines the control and configuration concept for his component, thus describing a solution space [2].

In order to adapt a product even more easily to new functional or design requirements, knowledge-based design (KBD) and knowledge-based engineering (KBE) extend this approach. In this context the overall goal is to transform a design problem into a configuration problem, using not only dimensioning or calculation formula but, e.g., design rules, manufacturing restrictions, and reasoning [3]. This offers the opportunities to widely automate routine design tasks in mechanical engineering on the one side. On the other side, knowledge capture and reuse raise the quality of design artifacts and partly decouple the design results from the designer's experience. As side effect, a reduction of time and costs in the development process is visible [4]. This is especially necessary in business models that rely on tailoring products to a customer's needs, like mass customization [5].

1.1 Motivation

In spite of the potentials and the fact that KBE is discussed in academia since more than 20 years, it still has not achieved a remarkable breakthrough. Existing approaches are predominantly limited to niche design activities or to aviation and automotive engineering [6]. From the authors' point of view, this does not originate from missing KBD functionalities in contemporary CAD systems because the technologies are at hand (refer, e.g., to [7]). As well there exist a number of process models for creating KBE applications like CommonKADS [8] or MOKA [9]. But most authors do not present concrete design methodologies, modeling principles, or detailed application examples. To date, no scientific books can be found that are dedicated to CAD-KBD. Additionally, a study of curricula in engineering design revealed that the setup, structured exploration and management of design solution spaces for configuration and optimization, is yet not present.

In the following paper, the authors want to narrow this gap and document their experience with the Knowledge-Based-Design-Lab which is held at the Leibniz University of Hanover for 5 years. The tutorial shifts the traditional modeling of mostly rigid geometrical product models to design automation and the implementation of configurable virtual prototypes within Autodesk Inventor Professional.

1.2 Structure of the Paper

The following Sect. 2 provides a brief overview over the study of the engineering design curricula of the German TU9 universities. Section 3 contains a review of problem-, project-, and case-based learning in engineering design. Section 4 then presents the current approach of the *Hanover Knowledge-Based-Design-Lab*, giving details about educational objectives, learning sequence, and examples. Closing the paper, Sect. 5 contains a brief summary and outlook.

2 Knowledge-Based-Design in TU9 Curricula

In order to examine existing engineering curricula with respect to solution space development using knowledge-based design and engineering, the first step is to define the relevant keywords for the search. Therefore we compared different definitions of KBE. As an example, Chapman and Pinfold [10] state that "*KBE represents an evolutionary step in computer-aided-engineering and is an engineering method that represents a merging of object-oriented programming, artificial intelligence and CAD-technologies, giving benefit to customized or variant design automation solutions*." The comparison leads to the following search items:

– knowledge-based design
– knowledge-based engineering
– automation
– variant design

In the following, these terms were searched in the engineering curricula for bachelor and master studies of the German TU9 universities. The TU9 is an alliance of the leading German institutes of technology, consisting of the RWTH Aachen, TU Berlin, TU Braunschweig, TU Darmstadt, TU Dresden, Leibniz University of Hanover, Karlsruhe Institute of Technology, TU Munich, and the University of Stuttgart.

The study showed that the majority of six of the TU9 does not offer any courses that deal with at least one of the mentioned keywords. Three universities (Leibniz University of Hanover, Karlsruhe Institute of Technology, University of Stuttgart) teach the fundamentals of knowledge-based systems (in general computer-aided problem-solving) and knowledge-based engineering systems in line with lectures about computer-aided engineering. Additionally, master students of the TU Munich are taught about the modeling of knowledge-based systems in general, but the link to geometry modeling is not present. At the Karlsruhe Institute of Technology, Leibniz University of Hanover, and University of Stuttgart, the fundamentals of variant design through parametric CAD are taught as part of basic CAD tutorials but with no emphasis on design automation. Actually, only at the Leibniz University of Hanover design automation through knowledge-based design is implemented in a tutorial where students work in groups together in order to transform a design problem into a configuration problem.

3 A Review of Problem-, Project-, and Case-Based Learning

From the authors' point of view, the classical "*chalk and talk*" approach in form of deductive lectures is not suitable for teaching knowledge-based design. Making KBD work involves many different skills beneath learning the trade of constraining parameters or defining design rules. As such stand identifying and justifying the need for automated design solutions acquire the relevant knowledge from human and nonhuman resources and working together in a team of future knowledge engineers to generate the desired results, to name only a few.

There exist a number of different *inductive* teaching methods that transfer the responsibility for learning and content to the students [11]. The point of origin is, e.g., a real-world problem the students have to solve or a case study or experimental data that they have to draw conclusions from. Therefore, they identify needs and discover relevant knowledge (guiding principles, rules of thumb, standard procedures) by themselves in order to apply this to their given task. The instructor supervises this process and provides necessary information where needed, assuring that the learning objective of the course is achieved. Among others, problem-, project-, and case-based learning approaches may be applied to engineering education [12].

Problem-based learning dates back to the 1960s where the concept was implemented for the study of medicine. Basically, a student has to pass through three phases: first, he is encountered with the problem, and professional reasoning skills are developed together with a tutor. In the second phase, the student performs a self-directed study in order to acquire the knowledge relevant for the solution. In the third phase, this knowledge is applied to the given problem in presence of the tutor again, and the learning process is reflected [11].

In that approach, a problem statement should be open-ended, ill-structured, and of authentic kind. Students may work in teams; the class time is used either for group reporting, impulse lectures, or class discussion. From a cognitive point of view, a major benefit of problem-based learning is its capability of guiding students through the discovery of problem solutions and reflecting the learning process. The focus is on knowledge acquisition [13].

Project-based learning has many similar aspects since it also involves teams of students that have to identify solution strategies to a given problem statement. But in opposite to problem-based learning, a project is of wider scope, may contain multiple problems, and leads to a kind of end product (a design, a simulation, etc.). To complete the project, the students have to apply knowledge that is either previously acquired or taught in accompanying courses [14].

Case-based learning (and teaching) dates back to the end of the nineteenth century and is frequently used in schools of law, medicine, and business administration. Regarding engineering education, case-based learning relies on engineering activities, problem statements, or situations that reflect real-world problems as well as the background and complexity encountered by engineers today.

Compared to problems in problem-based learning, a case is usually well structured, involves a rich contextual background, and is used to drive students to apply already existing knowledge. The typical setup of a case analysis may be described as (1) case review, (2) problem statement, (3) gathering information, (4) development of alternatives, (5) examination and argumentation of identified alternatives, (6) choice of possible solutions, and (7) evaluation [12].

4 The Hanover Knowledge-Based-Design-Lab

The Knowledge-Based-Design-Lab is conceived as project-based learning environment that incorporates problem-based and case-based elements for subtasks.

Students may take the course from the fifth bachelor semester on; it is accessible for both bachelor and master students. Mandatory preconditions are experienced use of Autodesk Inventor and the completion of the *design projects I* and *II*, where the students experience technical drafting, computer-aided design, and design methodology while designing devices and gears.

Depending on the amount of instructors, 20–30 students are accepted for one class, which are divided into groups of 4–6 people. Each group is guided by an instructor, who provides additional information and functions as subproject manager. Taking into account that the instructors contribute to the design project as well, the design automation task covers approximately 800–1200 man hours in total.

4.1 Educational Objectives

The following is an excerpt of the course and module catalog of the faculty of engineering at the Leibniz University of Hanover:

The Knowledge-Based-Design-Lab provides skills for knowledge-based design of products within Autodesk Inventor. The knowledge from the design projects and the design theory are thus placed in a higher context and used for design automation. The students:

- *model parametric parts and subassemblies*
- *learn the iLogic programming language and implement design rules into parts and assemblies*
- *use equations for constraining parameters*
- *create simple product configurators*
- *apply the acquired knowledge to a design task within teams and reflect the group work*

4.2 Course of Action

The tutorial is organized in ten appointments of 90 min of presence time each. The same amount of time is recommended as preparation and wrap-up for each group outside class. The appointments have the following content:

1. Get-together and iPart parametric part families
2. Parameter constraining, equations, and skeleton techniques
3. Spreadsheet-driven design and iLogic
4. Group formation, presentation of the design project, and initial information gathering
5. Subproject assignment and impulse for knowledge-based systems development (usually about MOKA)
6. Group work and reporting: Parameter planning
7. Class discussion: Agreement on design interfaces and the global configuration concept
8. Group work and reporting: Dynamic assembly concept
9. Group work and reporting: Subassembly modeling
10. Final assembly, testing, and review of the learning process

The following subsection contains a detailed overview about the content of the third appointment that is dedicated to spreadsheet-driven design and the iLogic rule language.

4.3 Spreadsheet-Driven Design and iLogic

In the third class time, the learning objective is to design a dynamic assembly that is controlled via a simple spreadsheet configurator. The assembly belongs to the category *simple machine elements*, where a shaft or a gear part is assembled together with standard parts.

Background. Besides constraining parameters via equations at placing dimensions, it is also possible to define constraints and design rules between multiple parts and assemblies by application of iLogic rules. iLogic has to be understood as programming language which is similar to script languages. Common constructs like if-then-else or select-case decision trees, while loops, the use of sub procedures and a class concept are available. As command library the snippets include code templates for almost every modeling context within Inventor. All parameters from every active component or feature can be accessed by the model tree within the iLogic rule editing dialog.

Figure 1 shows the iLogic rule editor. In the example two parameters *d0* and *d1* are linked to prior defined user parameters via equations, and the suppression state of a chamfer feature is related to a boolean parameter. In contrast to parameter equations, iLogic rules are not computed automatically at every rebuild of the

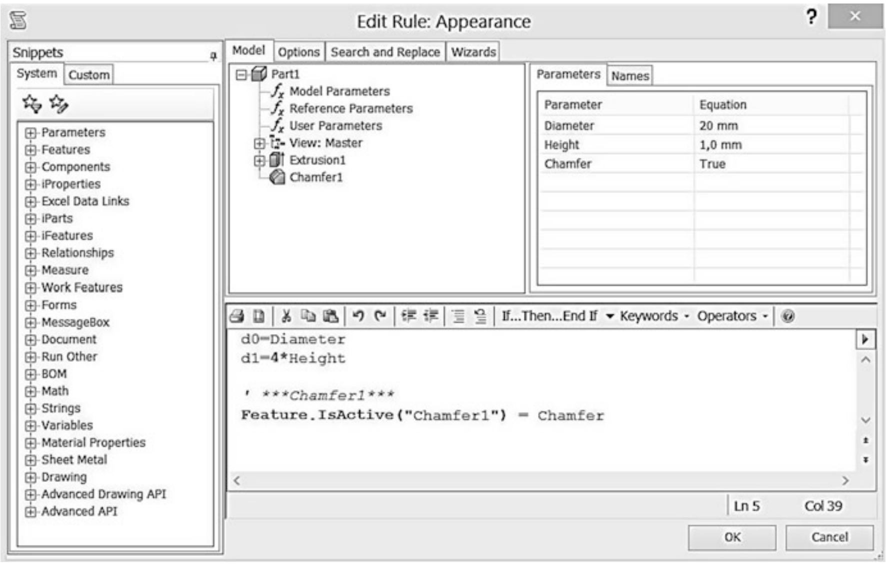

Fig. 1 iLogic rule editor

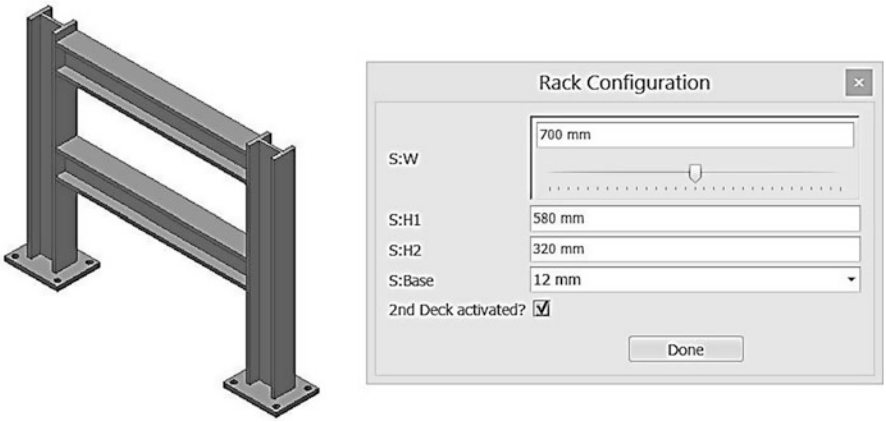

Fig. 2 Base frame – iLogic Form

model. The computation either has to be triggered manually or linked to certain events like geometry update, closing a file, etc. iLogic also allows to create a simple user interface so that the parameter change is not done in the parameter table but in an iLogic form (Fig. 2).

As option for dynamic assemblies, especially when extended mathematical and statistical operations need to be addressed, stands externalizing the parameter control into a spreadsheet application like MS Excel. The layout as shown in Fig. 3 has to be used since the format of an Inventor parameter is strictly defined but

Name	Value	Unit	Comment
S:W	700	mm	Width
S:H1	620	mm	Height Deck 1
S:H2	300	mm	Height Deck 2
S:Base	12 mm		Thickness Base Plate

Fig. 3 Inventor embedded excel table

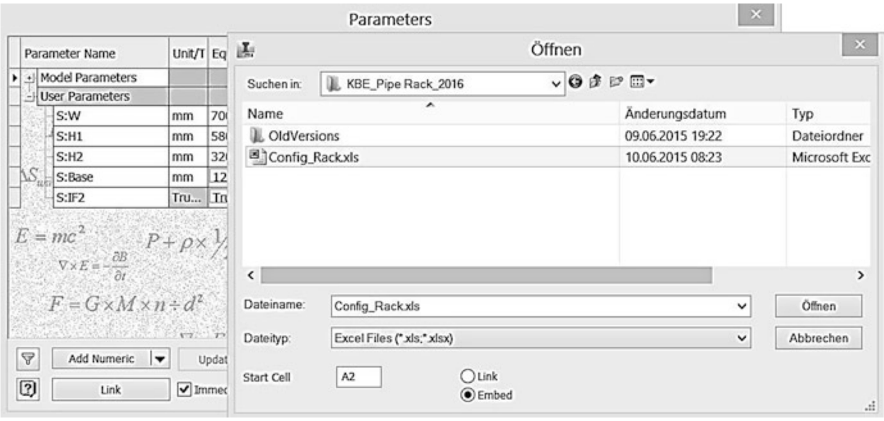

Fig. 4 Inventor table import dialog

additional columns and work sheets can be used for parameter calculation, storing parameters of standard parts or for user interaction (e.g., plausibility checks or interactive diagrams).

Afterward the parameters are listed as embedded parameters and can be linked via equations or design rules. The use of MS Excel is a powerful tool for creating easy-to-use design configurators (Fig. 4).

Execution. The class is divided into three parts. In the first 20 min, the instructor delivers an impulse lecture about iLogic and the embedding of excel spreadsheet files into Inventor part and assembly documents. This is flanked by a revision of useful excel commands and functions.

In the second part of the class, the students have to perform a case analysis. The given design consists of a shaft that is equipped with a ball joint bearing, a retaining ring, and two fitting keys (Fig. 5). According to case-based learning, the students first review the assembly and analyze the model setup and parameters.

As results the students discover that:

– the top-level assembly is steered by an embedded excel spreadsheet
– the spreadsheet contains mechanisms that calculate the geometric dimensions based on forces, internal stresses, bearing life, and the geometric interface to the neighbor parts that determine the length of the shaft

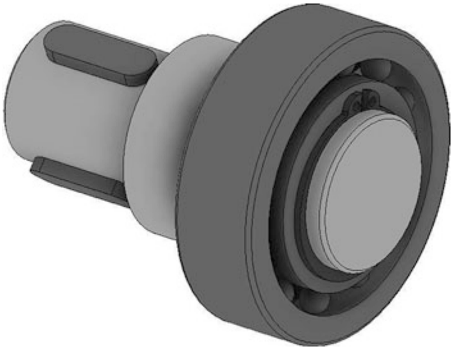

Fig. 5 Dynamic shaft assembly

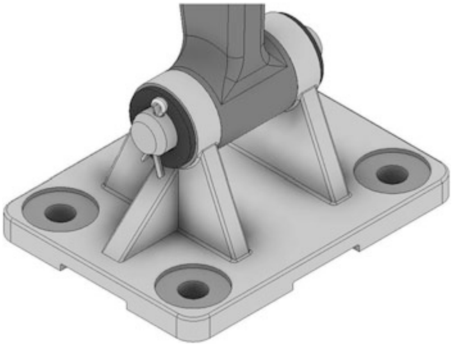

Fig. 6 Dynamic assembly of a bolted connection

- the spreadsheet does also contain information about allowed shaft diameters that correspond to the ball joint bearing, which is used as restriction
- global parameters calculated from the spreadsheet are transferred to the shaft via iLogic rules
- the shaft contains a parameter control for the groove where the retaining ring is placed and reasons whether one or two fitting keys are necessary
- all standard parts are implemented as iPart families
- an iLogic rule in the top-level assembly controls the choice of the right standard parts
- the rule is fired when parameters in the top-level assembly change

In this phase of the class, the instructors have a close look at the students' case exploration so that the task can be carried out in 25 min.

For the third part and the remaining 45 min, the students apply the previously acquired knowledge to a bolted connection (Fig. 6). They get parametric CAD models of the mount and the rod, iParts for bolt, washer and splint, and the necessary formulas to calculate the bolt diameter from given forces and to prove the strength of the connection. Parts from the spreadsheet and from the iLogic rules from the shaft assembly may be copied and adapted in order to save time.

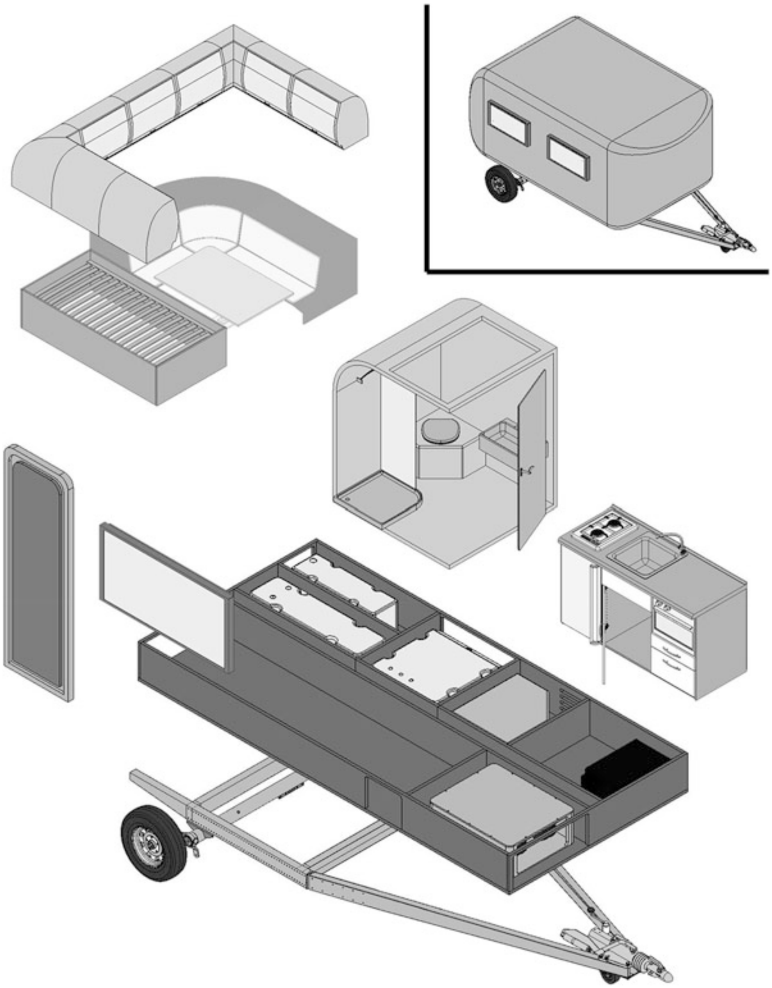

Fig. 7 Configurable caravan

4.4 Achievements

In this section we present two examples of student projects of the last years. In 2014, 22 students and 4 instructors worked on a configurable caravan (Fig. 7). The model consists of trailer, floor assembly, body with door and windows, kitchen, bath, and multiple furniture. Key features are as follows:

– the body's shape is adjustable via sketches
– the body trims the back of the furniture so that no collisions occur
– the outer shape of the upper shelves is modifiable

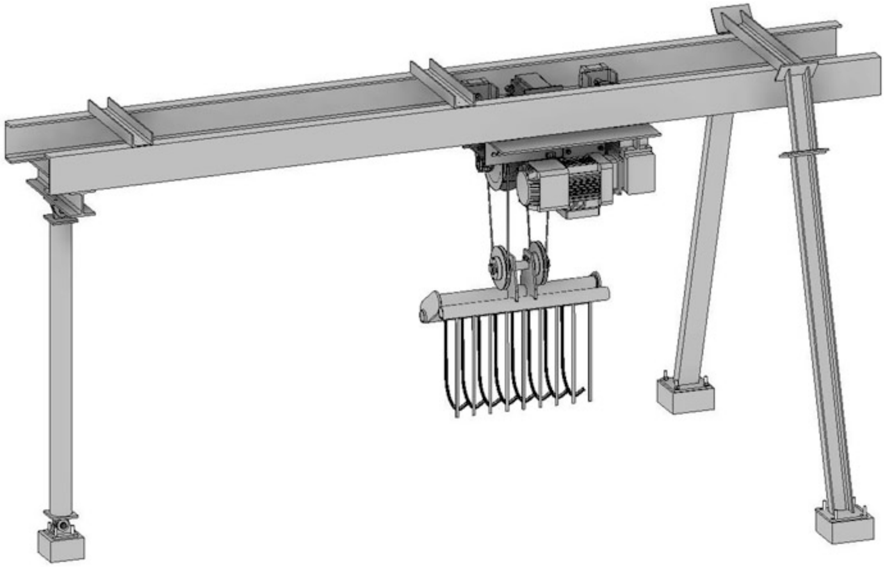

Fig. 8 Configurable trash rack cleaner

– kitchen and bath room have multiple options
– the trailer reasons about weight and center of gravity of the whole caravan and adjusts the position of the axle so the load of the hitch is optimal

The actual project in 2017 is a trash rack cleaner (Fig. 8), which is still in progress. Twenty-six students and six instructors develop the following functionalities:

– pathway and supports configurable regarding layout (linear or different levels)
– support size is calculated automatically
– lift unit completely calculated based on the weight of gripper and trash
– lift unit changes from single winch to pulley

5 Summary and Outlook

The Hanover Knowledge-Based-Design-Lab was founded in order to improve educating students in KBD. Based upon functions that are available in standard CAD systems, the students learn about parameter planning, constraining and parametric part and assembly models, the implementation of design rules, and simple configurators. Set up as project-based learning environment, the students work in teams to widely automate product design.

The results from the past 5 years are encouraging and should motivate to include this topic in the curricula of other technical universities as well. On the one hand, the results of the lab itself show a wide applicability of KBD in today's product development and the creativity and the potential of engineering students at the end of their studies. On the other hand, the engagement of the graduates to convey the taught knowledge to their future employers offers the possibility of directly transferring this topic into a wide application in industry and generates third-party projects.

In the year 2018, the Knowledge-Based-Design-Lab will get an even more prominent place in the curriculum of the faculty of engineering in Hanover since it will be embedded into the lecture "Knowledge-based CAD." The lecture and the affiliated tutorials then will be credited with 5 ECTS so that even more complicated CAD product configurators may be implemented by our students.

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Part VI
Mass Customization of Textiles and Fashion Products as a Special Field of Application

Fashion Apparel Industry 4.0 and Smart Mass Customization Approach for Clothing Product Design

Jocelyn Bellemare

Abstract Fashion Apparel Industry 4.0, which created what has been called a "smart factory," is now a paradise of real-time efficiency. With its work force and manufacturing ability, it is able to keep pace with fashion trends and work closer to market to achieve a mass customization program. This paper examines the potential of clothing configuration within the personalization and mass customization concept. Within the modular structured smart factories, cyber-physical systems monitor physical processes, creating a virtual copy of the physical world and making decentralized decisions. Even if some manufacturers have managed this approach successfully, others have only poorly grasped it. The increase in purchase returns for personalized and customized clothes both in stores and on the Web creates headaches for retailers because it affects their brand image, customer perception, and loyalty intention. The first problem is related to the 4.0 manufacturing aspects with measurements, adaptation of patterns, and flexibility in methods and manufacturing deadlines. The second is the lack of knowledge and experience on the part of the manufacturers to properly use the configuration systems. It has become increasingly important to understand how to create an approach for configurator implementation for the clothing personalization and mass customization program. For producers to make the most of this approach, they need to better understand what can be done in terms of clothing personalization and mass customization capabilities. We discuss custom clothing in conjunction with the effects stemming from the evolution of mass production practices. This led us to explore from different angles the problems related to the automation of standard sizes and integration of "fits" done in traditional ways as well as computerized ways with respect to product adaptation. In this paper, we also analyze the mass customization concept and propose technological and transparent operational approaches aimed at initiating useful discussions to better understand these issues and the new culture that has been created.

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Keywords Fashion Industry 4.0 · Smart apparel factory · Mass customization program · Sticky information · Fitting clothing · Configurator

1 Fashion Apparel Industry Faces Disruption from Outside

Leadership, consciousness, and coherence: three things to define the success of the fashion apparel industry. At the same time, disruption is happening within the industry itself as brands try to engage the consumer with the producer. The fashion industry faces the urgent need to rethink and strengthen strategy and identify alternative levers for sustainable growth. 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. Moreover, as apparel products now seem to have an even shorter life cycle, a phenomenon which is exacerbated by the introduction and implementation of new business models, businesses' commercial strategies face mounting tension. Nevertheless, fashion retailers and manufacturers are confronting growing pressures on their margins and stocks.

Over the past few years, increasing vertical integration and the relentless rise of online sales have created fundamental structural and mechanical shifts in the fashion and apparel industry. This situation forces fashion and apparel industry players to revise their organizational strategies in order to survive in this highly competitive market. Organizations must reinvent themselves and find new ways to satisfy their customers. In order to grow and to maintain the current level of employment and possibly increase it, clothing producers will need to develop new manufacturing strategies by orienting local production toward a flexible, quick-response system that allows for the fulfillment of various types of orders (small quantities, short deadlines, skilled labor, etc.).

Thus, it will become essential for businesses to implement new strategies that correspond to the reality of current markets, in order to keep up with the rhythm of short-cycle production. With this approach, manufacturing businesses need to focus on flexibility, adaptability, agility, and traceability. Managers in this industry need to take a close look at the current evolving market and, in some cases, quickly change or adapt their business models. To succeed at this, a company cannot rely solely on its popularity. Above all it must tap into the unique strength of its offering, because there's no room for error.

1.1 Fashion Apparel Industry 4.0 Challenge

Digital technologies create opportunities to develop new business models, serve customers in innovative ways, and run organizations more efficiently and profitably. The new challenge of the industry is the digital approach. Fashion Apparel Industry

4.0, called a "smart apparel factory," is the current trend of automation and data exchange in apparel manufacturing technologies. As a combination of several major innovations in digital technology, it includes the Internet of things, cloud computing, and cyber-physical systems that communicate and cooperate with each other in real time, used by participants of the value chain driving a new shift of change across the economy, with major implications for the fashion market – including RFID, sophisticated sensors, digital printing and fabrication, 3D product development, and more. The consequences for fashion industry leaders are clear: more than ever before, they need to refocus on a few truly distinguishing core capabilities to create sustainable value in the future.

1.2 Mass Customization Approach

Reviewing the writings on this subject tells us that paradoxically, at a time where the global keyword in most industries is standardization, the focus in the apparel industry is on "uniqueness." Today's consumers are increasingly demanding and will no longer settle for the mass offerings proposed by major retailers. They want what they buy to have a personal quality. The increased use of mobile devices due to convenience of the Internet is likely to influence consumer shopping behaviors, such as time spent in searching various channels and other ways in which they can use digital devices [1]. Add to this the strong influence the Internet and digital technology have on consumer habits and choices.

They are no longer satisfied with standardized products that force them to make compromises. The Internet influences customers' buying habits by creating needs that have to be satisfied instantaneously. At an increasing rate, people are losing interest in mass-produced items and are seeking a little piece of the manufacturer's DNA, that which makes the item authentic. They're looking for the experience, but not at any price.

In the clothing industry, these expectations not only imply having to constantly provide consumers with new options in terms of styles and colors but also to allow them to find an affordable well-fitting clothing item and make it available to them almost as rapidly as if it were a standard-sized product. In order to meet these expectations, clothing companies must now propose custom-made products. Brands that offer personalized products (mass customization) are taking over both traditional and online stores. According to McKinney et al. [2], this is made possible by identifying the key points of body measurement necessary to produce well-adjusted, well-fitting garments. However, being able to take these measurements effectively and efficiently is crucial. Although efficient and affordable technologies are available to provide a body scan, few businesses are able to meet the requirements of custom-made products for the following reasons: lack of reliability of the measures provided by the body scan, problems related to the transmission of a large quantity of data to potential manufacturers, and interface issues between the data generated by the body scan software and that used by patternmaking, cutting, and assembly. 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. Thus, for example, manufacturers will have to change their positioning from simple manufacturer to positioning solutions and service providers. This example demonstrates the profound changes that traditional clusters will have to make. It is precisely on this point that digital interventions will allow implementation of an agile organization. Nevertheless, mass customization somehow remains misunderstood or is rarely used by actors in the clothing industry mainly because of the widely variable measurements, the problems in adapting patterns, and the need for flexibility in manufacturing delays and methods. Many authors have produced research on mass customization; however, few of them have sought to identify the problems related to sizing and to so-called hidden data coming from the customers (ease allowance, fullness, etc.).

Our objective is to develop a configurator for clothing mass customization embedded in Industry 4.0, using computerized digital information systems, that could be used to analyze and decode measurement data coming from peripheral devices in order to identify the necessary information to produce a well-fitting garment. Hence, we need to identify the fundamental variables and data that are necessary to produce custom-made clothing. Parsimony in fundamental variables (length, circumference, density, textile matter) will allow us to significantly diminish the amount of data to analyze and send out in order to create an "intelligent" pattern within Industry 4.0.

2 Literature Reviews

The goal of mass customization is to efficiently provide customers with what they want, when they want it, at an affordable price. Inala [3] contends that mass customization has become a competitive strategy for businesses that want to offer personalized products. The more a business provides opportunities to personalize its products, the more competitive it becomes [4]. A mass customizer must first identify the idiosyncratic needs of its customers, specifically those product attributes along which the customer needs to diverge most [5]. When clothing was made to measure, each garment was cut and assembled for individual customers [6]. As a result, it provided a personalized fit (Workman, 1991). This type of production is what Pine [4] referred to as personalized and handcrafted production. Likewise, in order to be able to meet the demands of mass customization, all of a manufacturer's operations have to be based, according to Zipkin [7], on flexible processes that allow it to respond rapidly to customers' requests. More often than not, mass customization consists of, for example, assembling basic items according to specific orders.

Mass customization therefore becomes a crucial development solution for businesses specialized in garment manufacturing and distribution [4]. In fact, the demand for mass customization of clothing is only growing stronger. It has become possible thanks to the contribution of new technologies. Custom-made clothing requires a very thorough understanding of the expectations and specificities of each individual [8]. According to Pine [4], the success of mass customization rests mainly on a successful integration of the value chain. In some respects, businesses must accomplish a feat by performing well on two axes that are generally on opposite ends of the spectrum in most businesses: maintaining short supply lead times while offering custom-made products that correspond to clients' specifications. There are mass markets for some customized products – the emergence of mass customized apparel demonstrates that [7]. The main problem in mass customization is related to the preparation of products according to customers' requirements. Moon et al. [9] state that because of their lack of knowledge and experience, consumers do not know what they really want. Thus, it is important to simplify their request by offering them some guidance. Doing so not only requires knowing a customer's measurements and style but also obtaining information that he never reveals: what literature refers to as "sticky information." The term "sticky information" is defined by Von Hippel [10] as information hidden by a customer that provides, in certain cases, a company with a key competitive advantage and offers significant opportunities for innovation. For example, consumers know their needs and tastes better than manufacturers. It is therefore difficult for a manufacturer to obtain pieces of information that are either confidential or perceived to be so irrelevant that consumers reveal them sporadically, at best. This unknown data, like ease allowance, fit, proportion, and the like, is essential to the production of custom-made garments. According to Ashdown [11], they are the source of most purchase returns occurring in stores.

According to Rahman et al. [12], the Canadian market used price as an indicator of product quality and/or monetary sacrifice. Overall, the consumers were more concerned about the garment fit and style than brand name and country of origin. It is imperative for fashion practitioners to prioritize their resources and focus more on product research/design and prototype development. Fit, comfort, and fabric were strongly correlated except in the "fit and comfort" of the Canadian sample. In addition, durability, ease of care, and wardrobe coordination play a relatively less significant clothing evaluative role than many other product cues.

2.1 The Increase in Purchase Returns

According to a survey conducted by UQAM in 2015, the increase in purchase returns for clothes both in stores and on the Web in North America creates headaches for retailers because it affects their brand image. The survey also confirms 66% of Canadians claim that it is very difficult to find clothes that fit them perfectly and 82% of people surveyed find that sizes vary from store to store. As a result, it appears important for stores to know their clientele and to offer clothes that fit customers adequately in order to increase their volume of sales per customer. Thus, some problems associated with mass customization must be corrected by the garment industry. They are as follows: the templates (blocks) used to create basic patterns are not adequate; the size standards and measurement charts have become obsolete; the

Fig. 1 3D body scanning. (Optitex 2014)

sizing per territory/population rapidly changes; and some of the information hidden by the customer must be decoded by manufacturers. Faust and Carrier [13] contend that errors in measurements still prevail in the clothing industry. Even if a customer is given a sizing chart, it is still difficult for him to take accurate measurements on his own. Ashdown [14] has identified a few simple problems that might be encountered. For instance, when measuring waist circumference, it is necessary to stand straight in a natural position and to hold the tape measure parallel to the ground. A slight imbalance could result in errors of up to half an inch on the final garment. The main challenge occurs when measuring waist girth. Moreover, Park and Stoel [15] mention that data transmission errors taking place during the data transfer process create problems at the time of order. As for the 3D body scan technology (Fig. 1), a sample body scan sends more than 300,000 data items [16], which increases the complexity of selecting valid data in order to obtain reliable information.

Both methods (manual or 3D body scanner) of measurement have their strengths and weaknesses. For some authors, the biggest strength of the manual measurement is its ability to identify incoherent measurements, while its most important weaknesses are the labor costs and the imprecision caused by human error when transcribing data [17]. On the other hand, the strengths of 3D body scanning are the speed and the low cost (nowadays), while its main weaknesses are in the measurement inconsistencies due to movement [18], the lack of accuracy when compared with manual measurements [19], and the difficulty in obtaining correct measurements based on feet position, for example [20]. Accurate body measurements can be difficult to obtain with 3D body scanning due to factors such as posture, landmark indications, instrument position and orientation, and pressure and tension exerted [17]. Ashdown [11] indicates that computer systems need to accurately generate the information coming from both the patternmaking software and from the body scan. Issues arise when size charts and fit levels for different body types are not clearly established from the start. The key to success lies in the development, architecture, and support of computer systems used to generate data based on individual body dimensions for patternmaking software, which need to be adapted individually. Despite the fact that all these approaches aim to produce apparel as accurately as possible, it appears that the large number of constraints makes it difficult to find a compromise between performance, accuracy, and technicality during the production process.

2.2 Smart Configuration for Clothing Product Design

Configuration is an essential aspect of mass customization because it creates the possibilities to guide customers as they are making choices. Recently, a number of mass customizers have connected their sales configurators with social software applications and this is not surprising, as social software enables an interactive and socially rich shopping experience, which makes shopping with a mass customization toolkit more similar to retail shopping [21]. Here (Fig. 2), configuration processes play a crucial role in managing this task by providing customers with support and navigation in co-designing their individual product or service.

Product configuration systems play an important role in supporting the mass customization paradigm, as they help determine the degree of personalization that a business will offer. Mass customization does not equate to an increase in costs. According to Piller and Blazek [5], using a configurator could significantly reduce costs, since its Web-based technology diminishes the time required to take orders, and the application of toolkits for customer co-design may be the most used approach to help customers navigate choice in a mass customization system.

In the current context, businesses use catalogs and manual production methods. Interactive individual clothing catalogs provide a predefined and limited number

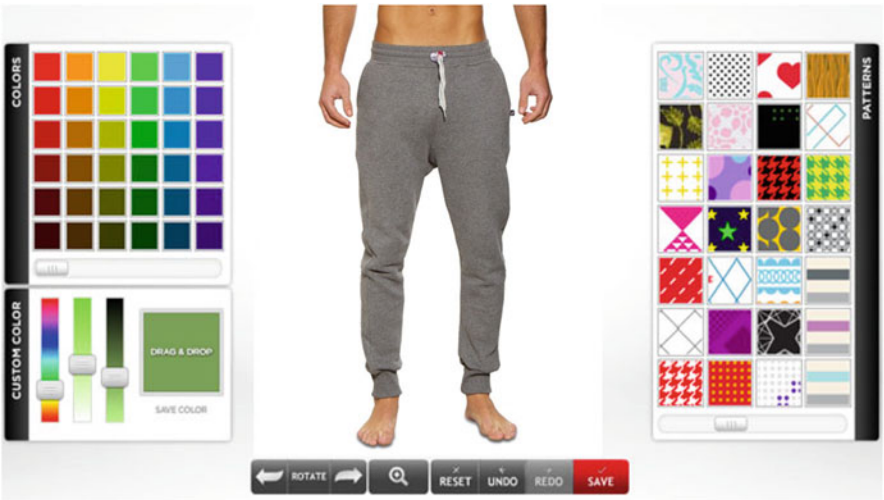

Fig. 2 Mass customization configurator for clothing

of combinations for a product without necessarily fulfilling all of a customer's specific needs. Manual configuration, on the other hand, essentially relies on human expertise and necessitates competent and highly skilled workers [22]. However, a lack of expertise eventually requires investments in terms of time and effort; moreover, it forces employees to keep up to date with frequent technical changes and improvements.

At the same time, many industrial companies will need to develop digital skills sets around creative digital strategy design, technology, architecture, and user experience design. As a result, the smart configuration of a product to meet a customer's requirements can become a complex task, which gets more demanding as the number of components and options increases. When the configuration requires numerous variations, the possibility of making errors also rises, which can result in production delays. Mass customization creates various technical challenges that need to be overcome before mass customized garments can be produced.

The technological risks associated with a configurator project are essentially related to the development of a system that can share and process data and parameters (the parameter configurator) originating from various sources such as the data entry tools (e.g., the body scan), the basic garment patterns, the marker-making software, the automatic cutting table, and the administrative and financial data. In short, none of the existing technological systems seem to provide a solution for mass customization in the apparel industry. A product configurator must be used along with a high-performance technological platform so as to allow for interaction between customer and manufacturer as the product is designed. Using virtual reality (VR) technologies (Fig. 3), 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 [23].

Fig. 3 Shopping with an avatar and virtual fitting. (Avatar 3D Marvelous Design & Virtual Fitting Fits Me 2014)

According to Kwon et al. [24], online self-customization (OSC) enables customers to design a product tailored to their preferences and needs via the online platform. The successful OSC experience goes beyond simply increasing a consumer's choice in preferred fit; it provides an opportunity to develop a meaningful relationship with customers by allowing them to embed their sense of self into the customized products and thus identify themselves with the products. The most important mass customization prerequisite is the understanding that mass customization itself is a highly customized strategy; you cannot imitate someone else's successful mass customization strategy [25]. If prime producers want to make the most of this prospect, they need to better understand what can be done in terms of clothing mass customization so as to formulate an appropriate strategy on how to use their measurement configurator. This research project will provide tools for fashion businesses that will allow them to gain a competitive edge through custom-made and short lead-time projects.

The opportunities created by the absence of such a service or system need to be used by businesses in this industry to reposition themselves on the garment and apparel markets, both locally and internationally. This research offers great possibilities in terms of innovation and could constitute an outstanding opportunity for several actors in the apparel industry. Even though the local garment industry and that of emerging countries face each other on an uneven playing field, the local industry possesses a technological environment that could give it a significant advantage.

3 Methodology

The first stage of this research project is a preliminary study of the fundamental variables and data needed to produce a custom-made garment. This first step will allow for the production of a study which is itself an integral part of a larger research project in Industry 4.0. The proposed approach will aim, in part, to identify the fundamental variables and data essential to the fabrication of custom-made apparel. After this result has been submitted, the data obtained will be analyzed, which will allow for the creation of a product parameter configurator.

Moreover, in the near future, we will assess the modalities of implementation of this technology and its progressive use in the fashion and garment industries. The preliminary phase of this research project will take place in a manufacturing environment specializing in men's fashion. At first, we will study the mass production and custom-made environments that exist in this industry. Next, we shall analyze three pants models provided by manufacturers specialized in menswear. Each pattern will be analyzed and dissected in order to assess the fitting and grading methods used in relation to size and type of textile. From this first study, we will formulate a hypothesis on the fundamental variables needed to produce a garment using mass customization. In order to validate the fundamental variables that will enable us to create our configurator, we will conduct a study of the process involved

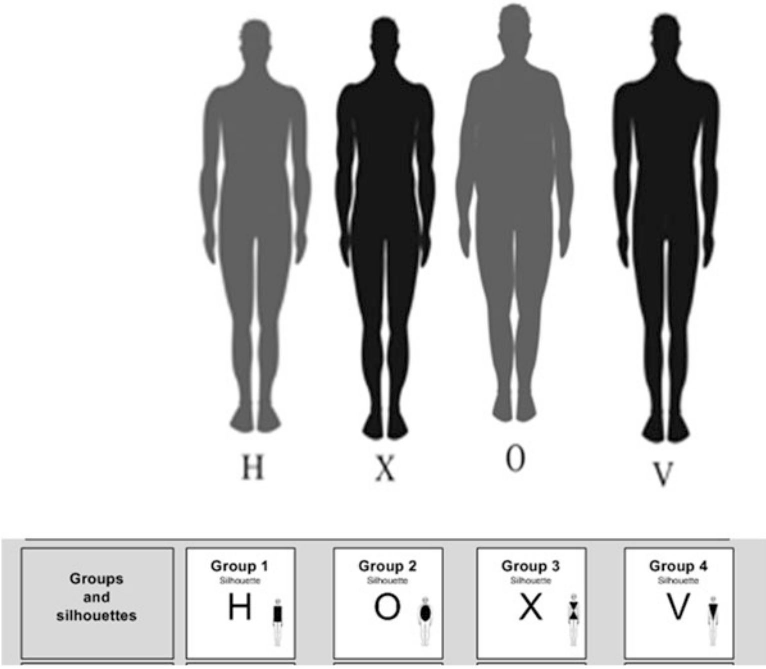

Fig. 4 Analysis of shape processes and methods

in body measurement (length, circumference, density, and stature) using both a body scan and manual measurements. We collected complete measurement data for 60 male subjects, aged 18–69.

In the same group of 60 men, 12 men will be recruited to allow us to model the variables and data linked to a production model that is part of a real rapid manufacturing process. In order to facilitate research based on individual shape groupings, we will use figure types represented by the letters H-O-X and V (Fig. 4) to categorize different types of silhouettes and redefining silhouettes from Rasband and Leichty [26]. Four morphotype groups will be made up of men (of different stature) wearing a size 40 jacket and trousers of sizes 32–38. This innovative method significantly improves the recurring problem in the industry regarding classification systems of normalization.

It will then be possible to validate the data through our configurator and produce garments using rapid prototyping. A thorough examination of the clothing items produced will be carried out during the fitting phases in order to analyze their "fit." This will allow us to determine which variables appear to be problematic. Mass customization offers a new business model and growth opportunities for small manufacturing businesses and clothing companies. Indeed, from mass or large volume production, businesses in this industry will be able to profit from this value-added advantage. According to Zipkin [7], this type of production will be possible on a large scale because new technologies will become more easily accessible. This project originated from the idea of creating the "optimal" product configurator which would have the capacity to efficiently translate customers' desires and associate them with their anthropometric and anthropomorphic characteristics.

4 Results Analysis

It appears obvious, following our measurements and interview activities involving 60 male individuals in an integral part of a larger research project, that the single pattern with respect to standard sizes is inadequate to meet the needs of the population. Personalization, therefore, is deemed to have a great future within the apparel industry.

Based on measurements systematically made on several pairs of pants, it appears that manufacturers have a major issue with respect to consistency in their products, not to mention that the underlying patterns are far from perfect. Based on this data, three different pairs of pants of the same quality, brand, and manufacturer will feel different on an individual. Independent of our approach to mass customization, we are attempting to solve this problem through this research because it is useless to try to find the perfect pattern for a given individual if the manufactured trousers do not conform to the pattern. In addition, following our measurement activities and meetings with master tailors, it appears that the measurements taken manually or in an automated fashion by body scan will not suffice to guarantee a minimum fit criteria when it comes to custom trousers for given customers. Other types of data are determined essential and more important than measurements. A particular approach to mass customization will require the acquisition of important data concerning fit, habits, and choices. This is confirmed (Fig. 5) following our meetings with North American patternmakers and manufacturers. When analyzing the process of creating patterns for different sizes from a master pattern, it appears that it would be very difficult to create a specific pattern for every customer. This type of fit pattern automation is deemed neither feasible nor necessary.

Analyzed results of the 60 individuals sampled show that we can identify approximately 12 customer profiles for every size. It would therefore be needed to design from known data not 1 but 12 patterns for each size, to accommodate the entire population with pants that would fit just as well as custom-made ones. The issue with mass customization would then rest on rapidly identifying the customer profile (Fig. 6) from the 12 standard profiles and producing a pair of pants from the corresponding pattern.

Tests made with respect to neural network aspects show that it is possible to automatically classify all individuals with relatively fewer sizes than those that are conventionally used (only 65% of typical sizes), however adding information from body analyzer/weight data, including fat and bone mass data (in the form of lean body mass statistics), body water percentage, and data concerning fit perception.

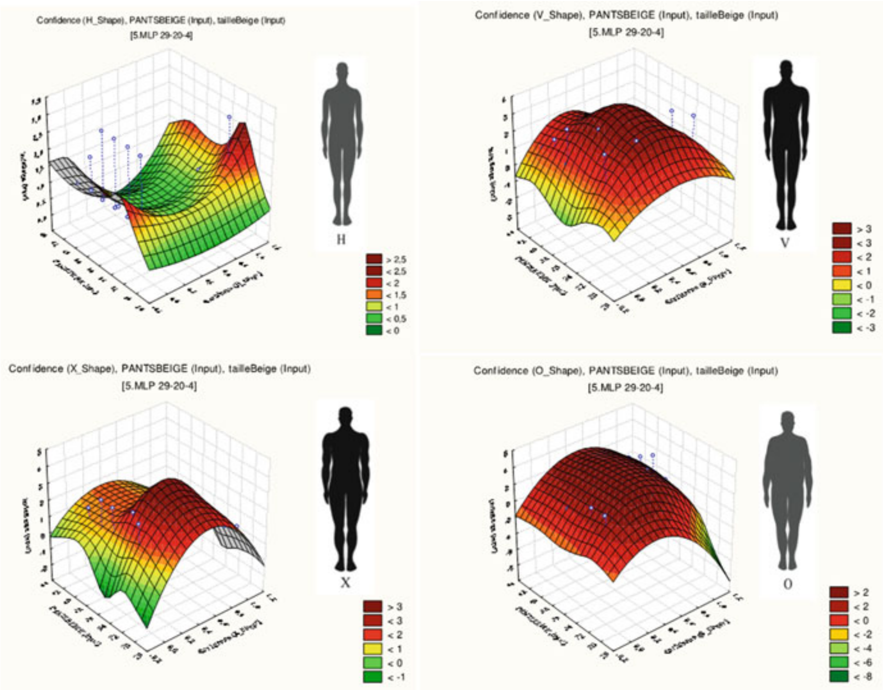

Fig. 5 Result of action and assessment of technological simulation tools used in the industry (cluster *fit*)

Fig. 6 Neural network and profiles

hidden neuron 10 --> SHAPE	-0,32745	H	Skinny
hidden neuron 6 --> SHAPE	-0,093516	H	
hidden neuron 8 --> SHAPE	-0,03338	H	Slim
hidden neuron 4 --> SHAPE	0,02314	Y	
hidden neuron 3 --> SHAPE	0,10598	V	
hidden neuron 5 --> SHAPE	0,190547	V	Athletic
hidden neuron 9 --> SHAPE	0,191697	X	
hidden neuron 1 --> SHAPE	0,240553	X	Strong
hidden neuron 11 --> SHAPE	0,305938	A	
hidden bias --> SHAPE	0,379991	O	
hidden neuron 2 --> SHAPE	0,435701	O	
hidden neuron 7 --> SHAPE	0,752189	O	Obese

On the whole, these results allow us to envision the logistical aspects within an installation that would use mass customization methods. The methods also become different for patternmakers, since instead of creating one pattern for each type (i.e., a master pattern for size 32), 12 patterns for each silhouette type would then be created.

Then, the same extraction methods for grade units using master grade units would yield the 12 patterns for each grade. Thus, by obtaining a body scan through Kinect Xbox 3D and data from a short survey/questionnaire, the manufacturer will then automatically obtain the silhouette data of target customers.

5 Discussion

Currently, tests with a configurator confirm the validity of our variables and the future potential for rapid prototyping via mass individual production and assurance of well-fitting garments via online request. This method can be applied for professional, commercial, technical, and mass consumer apparel. Through this work, it is also seen that it would be beneficial to label ready-to-wear trousers with silhouette-type information that best displays the style. This would no doubt allow the customer to filter more quickly through non-desired pairs or models. This simple approach provides new perspectives with respect to new and interesting concepts such as "fitthinking" theory for this industry, which could serve well in future tasks. This project offers numerous innovative possibilities and could provide a major opportunity for those implicated in the Fashion Apparel Industry 4.0.

More than ever before, those companies need to refocus on a few truly distinguishing core capabilities to create sustainable value in the future. After discussion and meeting with experts from the sector, we are able to define the priority of five key success factors for Fashion Apparel Industry 4.0: (1) customer excellence focus (the voice of the customer) and brand performance profile, (2) seamlessness in the omnichannel user experience integration, (3) renewed focus on physical retail, (4) operational excellence and innovation, and (5) process integration and traceability. To remain strong and competitive, a company has to demonstrate its capacity to adapt in terms of creativity, production, quality, timing, and price.

These findings should encourage the actors that make up this industry to readjust. In an age where innovation and technological developments play an increasingly crucial role in counteracting the effects of lower wages found in other countries, the objective of this research is to demonstrate the importance of implementing mass customization and rapid manufacturing systems adapted to the needs of all players in the clothing industry. If the vision of Industry 4.0 is to be realized, most business processes must become more digitized. A critical element will be the evolution of traditional supply chains toward a connected, smart, and highly efficient and agile supply chain ecosystem.

6 Conclusion

Digital capabilities are vital for moving forward with Industry 4.0. Apparel industry businesses must be proactive and adopt and adapt to new mindsets and management tools and digital culture 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. Mass customization offers much potential for extending brand awareness, acquiring new markets, and generating profits.

However, as stated, in order to do so, manufacturers must adjust their business practices and clearly define the limits of their operational strategy so that they do not radically alter a structure that took years to build. Mass customization must not be seen as a strictly short-term marketing strategy. When introducing new products or practices, a brand must be in synergy with its new offers, even if the company initially loses money. Manufacturer 4.0 must commit to sustainable development with demonstrated leadership, vision, challenges, directions, areas of intervention, and objectives as "clear as possible," in order to be an example to follow.

Moving forward with Fashion Industry 4.0 digital capabilities is important for industrial manufacturers. However, a gradual step-based approach is essential. This includes planning strategy, creating initial mass customization pilot projects, considering how you can best organize data analytics, and developing complete product and service solutions for customers. Industry 4.0 will be of significant benefit to those companies that fully understand what it means for how they do business. If actors in the fashion and clothing industry accept this change of direction, this project could evolve into an extremely competitive business model, which could also represent a viable option for companies in different sectors.

From the start, mass customization needs to directly involve customers in the designing and manufacturing phases. Furthermore, this customization model with Industry 4.0 must provide opportunities to generate savings by reducing stocks and allowing for better integration of all actors in the supply chain. Mass customization offers possibilities to reach, or even surpass, customers' expectations. Therefore, it needs to provide a knowledge base of consumers' needs and preferences and thus create opportunities for market segmentation and market targeting. Fashion Apparel Industry 4.0 and smart mass customization approach with digitization makes the supply chain more efficient, agile, and customer-focused.

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Individual On-Demand Produced Clothing: Ultrafast Fashion Production System

Daniel Buecher, Yves-Simon Gloy, Bernhard Schmenk, and Thomas Gries

Abstract In the textile and clothing industry, global value-added networks are widespread for textile and clothing production. As a result of global networks, the value chain is fragmented, and a great deal of effort is required to coordinate the production processes. In addition, the planning effort on the quantity and design of the goods is high and risky. Today the fashion industry is facing an increasing customer demand for individual and customizable products in addition to short delivery times. These challenges are passed down to the textile and clothing industry decreasing batch sizes and production times. Conventional clothing production cannot fulfill those demands especially when combined with more individual designs. Hence new sustainable and economical production concepts have to be developed. Together with the adidas AG, Herzogenaurach, a flexible and automated in-store production concept for knitted customized merino wool sweaters has been developed. With "Industrie 4.0" technologies, an urban and customer close production system has been developed. The analysis of the economical key performance indicators shows how such a new production system performs against a conventional production in Asia and where potentials are hidden.

Keywords Industrie 4.0 · Automated production · Production systems

1 Introduction

The target of every company is to satisfy customer demands. Especially the commercial sports clothing industry has to serve individual customer requirements. Textile products always have been and still are the defining attributes of people's appearance. Consumer's demands toward commercial clothing companies have been changing rapidly during the recent years. Two global megatrends have

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supported this change: individualization and digitalization. Individualization created demand for frequent collection changes, while still keeping availability high. Digitalization and Industrie 4.0 technologies supported the quick distribution of new trends and forced a higher amount of request during peak periods [1, 2].

Both developments represent a special challenge for the complexity management of global clothing companies. Frequent collection changes have to be managed by supply chain management (SCM). SCM needs to coordinate a growing number of products and suppliers on a global scale. The development of automation and Industrie 4.0 in the textile industry has offered alternatives to the distress of growing complexity. Due to the increasing share of intelligent systems within the process chain, textile manufacturers are able to reduce the impact of labor costs. In reaction to the reduced share of labor costs, new locations for production facilities have been enabled. Even a production in high-wage countries like Germany and the United States has become imaginable [3].

In order to evaluate the benefit of agile and flexible production systems, a comprehensive technology approach must be found and reasonably applied on new and existing production designs.

According to the "Aachener theory of textile production" (Fig. 1), which was developed at the Institut für Textiltechnik der RWTH Aachen University (ITA), this work evaluates different production systems for the textile industry regarding defined target values of production. In collaboration with the adidas AG, Herzogenaurach, Germany, two production processes, a classic knit production in Southeast

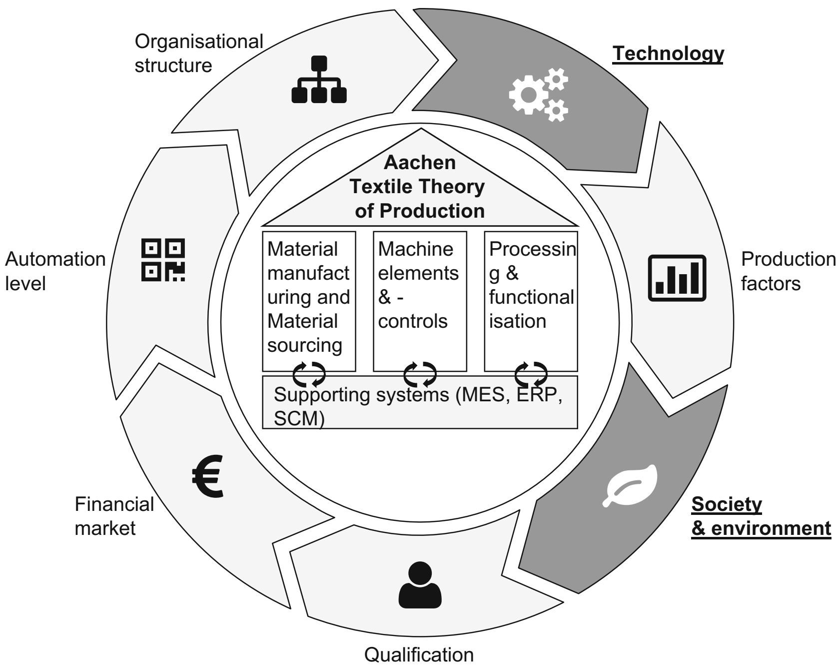

Fig. 1 Aachener theory of textile production

Asia and an Industrie 4.0 involving knit production in Germany, have been defined which build the foundation for a textile process analysis. The results can be used to make decisions on future production systems.

2 Concept Description and Requirements

The aim of the STOREFACTORY project is the development of an in-store fashion production adapting Industrie 4.0 technologies. Flat knitting is chosen as the main production process, as it offers the possibility to produce clothing without using joining technologies. Due to the higher product value, a knitted sweater is selected [4–7].

The in-store user experience consists of a body scanner and design stations, where the customer creates their individual fashion product. These processes are supported by a software system, which transfers the individual body measurements and the customer-created design into machine-convertible information. The production itself takes place on three flat-knitting machines followed by thermosetting as well as finishing equipment for the statutory labeling. Figure 2 outlines the customer experience in the developed concept.

Using a body scanner, the metric data of the customer is detected. The measurements guarantee a highly individual perfect fit. The metric data then is used in the design station, where the customer can design the patterning and coloring of his product himself. The colors are limited to the equipped colors on the knitting machines available. One machine can be equipped with up to three different colors, which can be combined in different proportions. When the customer is satisfied with his customization, the design is transferred to the knitting machine with the help of a converter unit. The converter unit not only takes into account the shrinkage through the thermosetting and the finishing process but also converts the metric data into machine data.

In order to plan the flexible production in an accurate matter and compare it to already existing production systems, an analysis proceeding needs to include a range of target variables, including companies' targets of maximized profit, customer satisfaction, etc. A proper evaluation method and visualizing production processes are based on the principle of the value stream. This model has been designed to identify different types of waste within defined production segments: transportation, inventory, motion, waiting, overprocessing, overproduction, and defects. This method captures the comprehensive process of the production and visualizes and rates processes as well as the physical flow [8, 9].

The analysis is started by detecting the value stream along the production chain. The process steps are separated into value-adding, non-value-adding, and information processes. Value is defined by the customer. The outcome of the process step will be valuable if the outcome provides a benefit to the customer. Value-adding processes in the textile production are, for example, knitting, weaving, mercerizing, dyeing, etc. Non-value-adding steps are transportation, waiting, overproduction, etc. By evaluating the process steps, problems and constraints can be identified. The

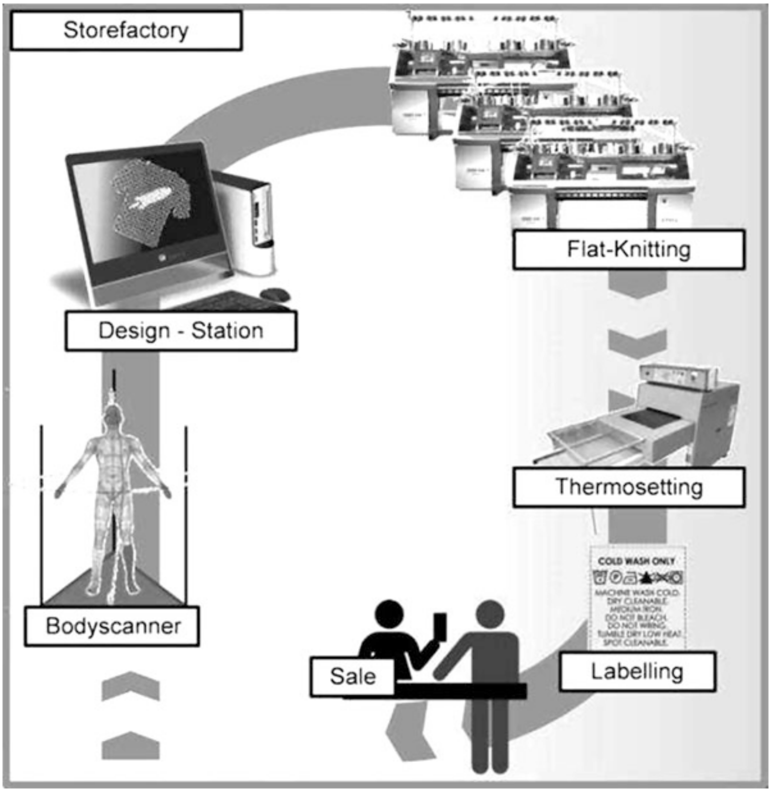

Fig. 2 STOREFACTORY customer journey

identification is supported by KPIs providing a quantitative rating on the current state of the process. The visual implementation of the value stream analysis is achieved with a graphic tool, called the value stream map. Value stream mapping consists of a visual qualitative and quantitative analysis. The analysis shows the structure of an entire production chain with flow of material, information, processes, and process abilities [10, 11].

Within the project two scenarios were examined. The conventional product, produced in Southeast Asia, is starting with the order from a marketing division, which is processed into a yarn order by the garment producer. After the yarn has arrived, the garment is produced and shipped back to the final destination market.

The in-store production starts as described with the measurement and the design selection of the customer, who is then giving the final production order. The customer data on design and size is translated by a manufacturing execution system into a machine-readable code. The knitting machines read the code and produce the textile as one piece. Afterward it is finished during several finishing steps. The technical details of the in-store production will be given in the following.

3 Thermosetting

Thermosetting is an expensive and energy-intensive textile process. Thermosetting is necessary to guarantee size accuracy and dimensional stability for knitted products. Depending on the material, different heat setting methods such as saturated steam or hot air are used for the fixation. The project aims to define the influence of thermosetting on mechanical properties and to analyze the correlation of heat setting parameters for wool and polyester.

With the help of a "one factor at a time" experimental design, heat setting parameters are varied. Mechanical characteristics and the material quality of heat-set and not heat-set material are evaluated to analyze the heat setting influence. The results show that shrinkage in wales direction is higher than in course direction. The tensile strength in course direction stays constant, whereas the tensile strength in wales direction can be increased by heat setting [12].

For the in-store production, a thermosetting process chain of steaming, washing, drying, and again steaming shows the best results for the used woolen material.

4 Converter Unit

To guarantee a perfect fit for the customer, the acquired thermosetting results have to be taken into account before the knitting process starts. Hence the shrinkage data is fed into a database. The so-called converter unit describes a software solution to apply the shrinkage on the individual body measurements (Fig. 3). In addition the converter unit solves the task of transferring the body measurements into knitting machine data.

Different approaches, using changing knit pattern combinations and sample sizes, have been analyzed of which two have been methodically developed, imple-

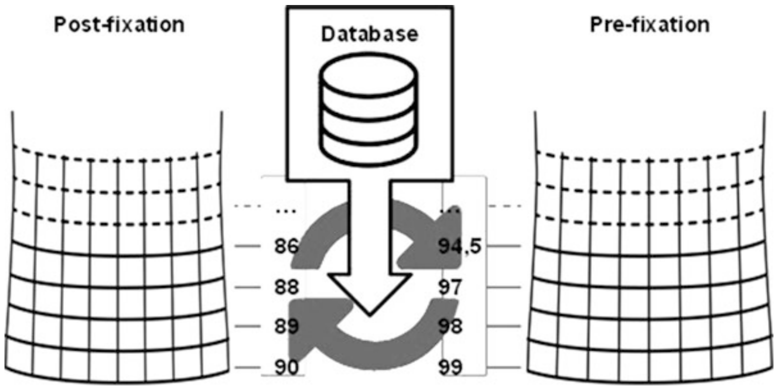

Fig. 3 Effect of shrinkage on body-fit products

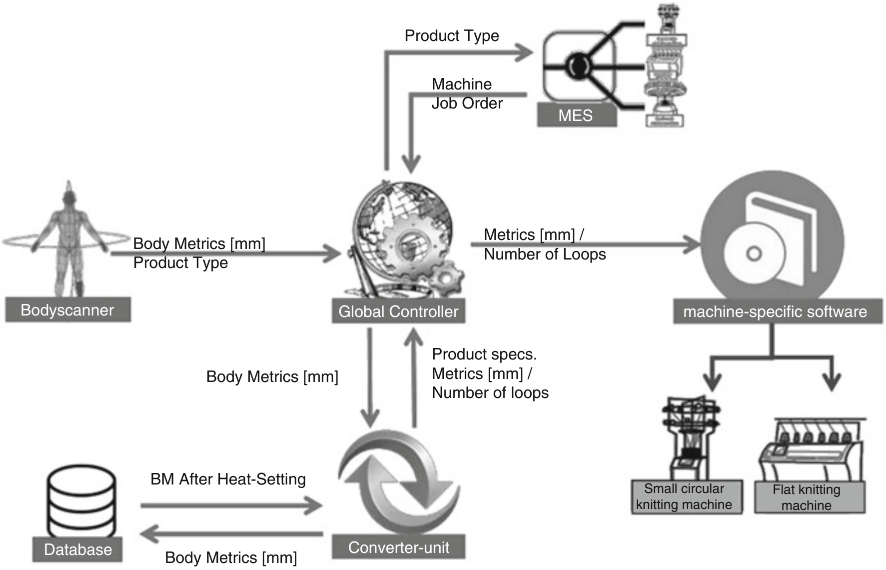

Fig. 4 Concept of the converter unit to transfer metric body scan data to machine-readable data

mented, and tested. The results do not differ in terms of accuracy. However the approaches show different results regarding look and surface feel. Based on those criteria, the best results have been archived adjusting yarn tensions directly on the machine.

The second task of the converter unit is to convert the metric data into machine data (Fig. 4). To fulfill this demand, proprietary software is used. E.G. for flat-knitting machines by company Stoll AG & Co. KG, Reutlingen, Germany a combination of the Stoll ShapeSizer, which convert the body-metrics the product contour, and the Stoll M1+, which generates the machine readable code knowing all knitting restrictions, are used. Together with the information from the body scanner and the thermofixation database, the machine-specific job is created. According to machine utilization, colorway, and technology, the most suitable knitting machine is chosen.

5 Results of the Analysis: Comparison of Local Production and Conventional Production

The production in-store is located close to the customer. Assumptions and expert interviews indicate that in-store production is more costly than the conventional process, so the profit is lower. The influence of the customer distance of conventional

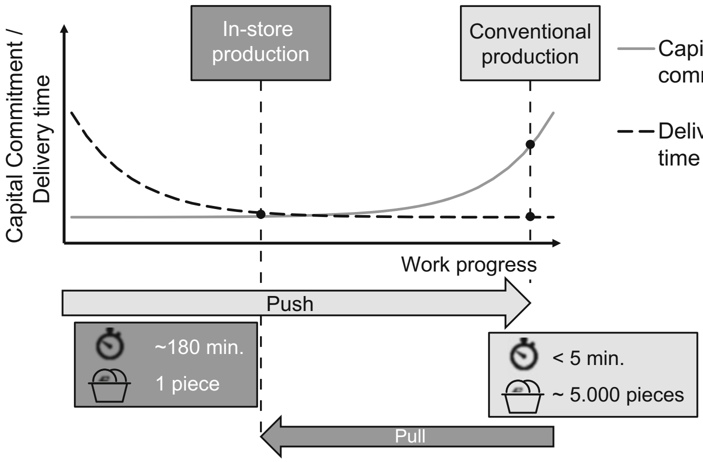

Fig. 5 Order penetration points for the in-store and the conventional production

and in-store production is visualized in Fig. 5 on the order penetration point (OPP). When facing different customer demands, the production structures have to change as well. The OPP in the work process also defines the type of order processing and affects the manufacturing form. The OPP defines the point of time the order is being processed with specific customer relation.

In the conventional process, a product is manufactured on stock and independent to the customer. Most of the work progress is already completed. The finished work process results in delivery times technically close to 0 min after the customer order because the product is instantly available. Guidelines support the buildup of capital in form of warehouse inventory. Sometimes the product is not sold directly after arrival in the designated country. The order amount is based on forecasts. If the forecast is wrong, the product won't be sold for the calculated price. This results in an actual risk that the product will not be sold for the originally estimated price because there may not be an actual demand later. In this case, the product has to be sold with a reduced price.

The value stream analysis shows the differences in production lead time of two knitted products. Both processes have the same starting and ending activity, beginning with the customer order and the customer delivery. For the conventional production, the whole process takes about 289 day. However the in-store production all in all takes about 175 min. Both cycle times are visualized in Fig. 6.

The comparison on the fractions of time used to create value with the product differs a lot, when the conventional and the in-store production are set against each other. Especially the comparison of the transportations as non-value adding time shows how the impact of delivery loyalty between both productions designs (Fig. 7).

While the in-store production is generating more value-adding process time, the production is more expensive.

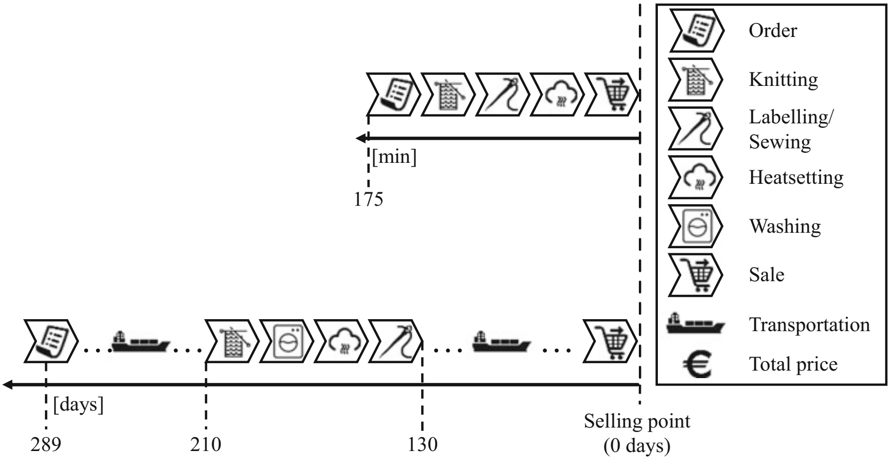

Fig. 6 Lead time comparison between conventional and STOREFACTORY production

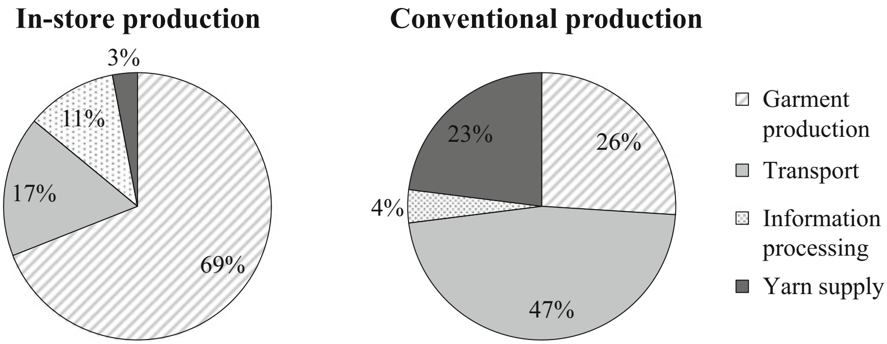

Fig. 7 Process percentage of both production designs

The impact on energy and CO2 emissions is captured considering the running times of the machines and even the standby times. The energy consumption is calculated for the entire production line. The calculation of the total energy consumption is used to calculate the different CO2 emissions for the in-store solution and the conventional process.

The results are based on a comparison of both process chains. By focusing on energy-intensive steps like the flat-knitting process, heat-setting, 3D scanning and the impact on less material waste for the in-store production. In the conventional process, flat knitting, heat-setting, washing, linking, and the impact of material waste were included. The in-store production process produces less CO2 emissions during production. About 40% less CO2 would be emerged into the environment, due to a different composition of renewable energy in Germany and Southeast Asia.

6 Conclusion

Within the STOREFACTORY project, an in-store fashion production line for individually designed and shaped woolen sweater has been successfully set up. With an approximately production time of 3 h from scan to fully finished products, the concept shows great potential facing the increasing customer demand for individual and customizable products. While the thermosetting analysis shows just a small impact compared to the impact of the correct finishing treatment, the desired fit can be achieved.

The converter unit exemplifies the necessary software solutions for the flat-knitting process and shows some generic concept to integrate different production processes such as circular knitting. The value stream analysis shows that the in-store production concept is economically suitable. In order to fulfill customer demands quicker and with lower market risk, textile producers must reevaluate their business model. Especially with rising labor costs in Southeast Asia, production in Europe becomes a more crucial option.

A conventional production process is characterized through high process times, high amount of planning, controlling efforts, and risks due to capital commitment in the make-to-stock process. The advantage of this process is low production costs due to low labor costs. A customized in-store production process is characterized through low capital commitment but high delivery times due to the make-to-order process. It was also shown that the in-store production saved about 40% CO2 in comparison to the production in Southeast Asia.

Both processes have been analyzed regarding costs and process times in order to define the challenges of a comprehensive textile process analysis. Based on the evaluation of the value stream analysis, both production systems can be evaluated and tested. The tool indicates the financial and temporal impacts of changes in the production specification. A future development would be the further collection of information through Industrie 4.0 applications on textile production processes in order to evolve usability. The evolution of the value stream analysis can provide a basis on decision-making for future strategically production decisions. Further research has to be conducted for different products, and production processes as well as a market analysis need to assess the customer experience.

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myShopNET: Personalized Consumer Goods e-Commerce Platform

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Abstract myShopNET is an EU COSME research project whose focus is on personalizable, design-driven, consumer goods. These products have unique requirements, due to its nature: for example, there is no physical sample before the good has been manufactured, and it is not manufactured before the customer co-design it, so there is not possible to see it or to try it before it has been purchased, requiring specific solutions to overcome these kind of problems, like fitting and sizing tools, pre-visualization tools, or co-design tools.

myShopNET main result will be a market-ready software platform that allows a user to create in less than 24 h a complete e-commerce solution specifically addressing the needs and requirements of the commercialization of customizable design-driven consumer goods, comprising specific modules for three types of products (footwear, shirts, and high-end fashion) and being easily expandable to new ones.

Keywords Co-design · Design-driven · e-Commerce · Footwear · Clothing

1 Introduction

1.1 COSME: Design-Based Consumer Goods Call

COSME is the European program for the Competitiveness of Enterprises and Small- and Medium-sized Enterprises (SMEs). It runs from 2014 to 2020 with a planned budget of €2.3bn.

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COSME supports better access to finance for SMEs, access to markets for SMEs, entrepreneurship, and more favorable conditions for business creation and growth. In a few words, COSME helps businesses to access markets in Europe (EU) and beyond.

We participated in the project *myShopNET* in the second call of the topic "design-based consumer goods," where 6 projects (from 24 submitted) were granted with EU funding. The project began in December 2016 and will last for 2 years, with the objective to pave the way to market of our proposed solution for the commercialization of design-driven consumer goods, focused at the beginning on clothing and footwear, but easily expandable to other ones.

1.2 The Consortium

To develop the myShopNET project, a consortium of four SMEs was formed:

- AluGroup S.L. (ALUGROUP) is a Spanish information and communication technology (ICT) consulting and developer (SME), providing advanced tools for consumer goods manufacturers and distributors (mainly in the footwear sector but also for other customizable goods, like glasses, bags, suits, mouth guards, etc.), focused on 3D visualization and co-design tools, integrated with advanced data management systems, smart fitting tools, and material creation applications. ALUGROUP is the project coordinator.
- Douëlou NV (BIVOLINO) is a Belgian SME with two core business units. There is a fashion department in charge of business-to-consumer (B2C) clothing, customizable shirts and blouses, supported by a Web shop ruled by a 2.5D product configurator connected to CAD and CAM applications. The user-defined shirts and blouses are produced through a fully automated production fulfilment system. The ICT department develops and commercializes ICT solutions for the fashion industry.
- Change of Paradigm Ltd. (CHANGE) is a British start-up company comprising expertise from fashion design and its convergence with technology. Their work is related to the implementation of novel methods to accurately capture physical properties of high-quality fabrics, photorealistic 3D simulation, personalized avatars, and almost real-time rendered simulation of clothing behavior, being used to provide high fashion Visualization as a Service (VaaS).
- Athens Technology Center SA (ATC) is a Greek ICT SME offering software solutions and services targeting multiple sectors like the media, retail banking, and the public sector, developing software solutions focused on content management, enterprise SW, Web apps, human resource management, e-learning, and mobile apps. Their activities span several countries in Europe, including CIS, Eastern EU, as well as the Balkans.

This consortium brings together expertise in ICT development and deployment, personalized consumer goods manufacture and distribution (specially focused on footwear and causal and high-fashion clothing), and B2C and business-to-business (B2B) models applied to consumer goods commercialization.

1.3 Problem and Solution

myShopNET is a project whose focus is on personalizable, design-driven, consumer goods: any kind of goods, not mass-produced, that require the collaboration of the final customer as co-designer of the product, for example, clothing, footwear, glasses, furniture, clocks, toys, etc. We consider product personalization as a way of implementing mass customization [1], in opposition to mass-produced consumer goods.

These products have very specific requirements, due to its nature: there is no physical sample before the good has been manufactured, and it is not manufactured before the customer co-designs it, so it is not possible to see it or try it before it has been purchased, requiring specific solutions to overcome these kinds of problems, like fitting and sizing tools, realistic pre-visualization tools, and friendly and easy-to-use co-design tools.

Although there are a lot of generic tools available for the creation of online shops (Wix, Volusion, Shopify, Yahoo Small Business, Magento, etc.), there isn't market availability of a specific tool adapted and focused on the particular requirements of personalizable design-driven consumer goods, which allow an easy and fast way (not requiring specific technical knowledge or abilities) to deploy an e-commerce experience, complete with connection to the supply chain, adapted to multimodal commercial strategies and seamlessly connected to major existing or new shopping sites, which offers an engaging experience to the consumers, involving them in the design process of the item they are going to buy.

Our proposed solution to this problem, the absence of an online shop creation tool focused on personalizable consumer goods, is myShopNET, a market-ready software platform that allows a user to create in less than 24 h a complete e-commerce solution specifically addressing the needs and requirements of the commercialization of customizable design-driven consumer goods, comprising specific modules for three types of products (high-end fashion, shirts, and footwear) and being easily expandable to new ones.

The situation, before starting the project, of our four partners and their respective ICT solutions related to the commercialization of personalizable consumer good showed quite different, unconnected solutions, with distinct levels of implementation and success in their own respective business sectors.

After the end of the project, we expect that the myShopNET platform will provide a common framework, for customers and vendors, to interact with the different personalizable design product modules, the existing ones for footwear and clothing and the new ones.

myShopNET platform is a common framework, a common way of enabling and supporting relationships between all actors of the chain (component and material providers, manufacturers, designers, distributors, logistic agents, and final customers) and a common way to solve the business requirements of this kind of products, with a similar set of tools, without losing the unique image (front-end and user interface), context and specificities of each one.

And this common framework has been designed under an open perspective, ready to be expanded with new modules, increasing nowadays existing tools to be able to attend the needs of new types of customizable goods: jewelry, toys, watches, glasses, furniture, etc.

2 Business Context

2.1 Personalizable Design-Driven Consumer Goods Market

Related to the field of application of myShopNET, we are dealing with e-commerce, and that means a huge market in Europe, corresponding to 296 million e-shoppers spending an average of €1450 per year [2].

Apparel and footwear are the leading product category in e-commerce both in EU and the USA. For example, nearly 50% of all Internet purchases in UK were clothing and sports goods, including footwear [3]. It is also the fastest growing category, with 20% annual growth in Europe.

The design-driven consumer goods represent a substantial part of European economy. The targeted industrial sectors represent a total annual turnover of €500bn, employing 5 million people in more than 500,000 companies across the EU-27 [4]. A good indicator of the increasing interest in personalizable items purchase comes from the fact that more than 35% of online consumers are interested in buying customizable co-designed products [5].

The proportion of individuals who ordered goods or services over the Internet for private use has risen and in 2014 reached 50%, an increase of 6% points compared with 2 years before. As such, the European Digital Agenda objective of 50% of the population buying online by 2015 was achieved a year early.

Of course, there are differences across Europe. More than two thirds of individuals in the UK, Denmark, Sweden, Luxembourg, the Netherlands, Germany, and Finland ordered goods or services over the Internet, whereas the proportion was nearer 1 person in 5 in Italy and Bulgaria and around 1 in 10 in Romania [6].

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2.2 Platform Clients

The clients of the myShopNET platform are those who want to open an online shop to sell personalizable design-driven consumer goods. And we divide the platform clients in three groups:

- Manufacturers of customizable consumer goods, willing to commercialize their products directly to the final client by means of and e-commerce website.
- Distributors of customizable consumer goods, with a variable degree of personalization, ranging from very short series manufacturing of exclusive and luxury products to individually manufactured ones – with or without co-design. These clients don't directly manufacture the items, they act as mere distributors and usually incorporate the personalizable or exclusive items inside a major distribution scheme (selling mass-produced products), being this activity complementary to their core business.
- Brick and mortar shop owners wanting to expand their core business, adding a new commercialization channel, and offering their products also in an e-commerce website, complementing their physical shop.

3 myShopNET Platform

3.1 myShopNET Conceptual Model

myShopNET conceptual model is based on a bi-directional interaction from both the product distributor and the product customer, with the modules corresponding to each type of design-driven consumer good:

- The goods seller can interact (via the Internet) with the *myShopNET* Web platform, by two separate ways:
  - Autonomous creation of the e-shop, available at any moment of the day and any day of the week (available 24 h/365d), without requiring special technical knowledge, including seamless connection to major standard e-commerce gateways (WooCommerce, Magento, Shopify, etc.).
  - Management of the e-shop, using a set of personalized management tools. These tools allow the e-shop owner to add goods, materials, components, and prices, connect to ERP (enterprise resource planning) and CRM (customer relationship management) by means of using common and standardized business documents, control the product production, manage shipment and logistics, track user interaction, etc.
- After creating the e-shop, the platform automatically deploys the e-commerce site, including the selected submodules or tools, allowing the customer to interact with the different available modules. The nature of the products we are selling

require the provision of specific tools that help the customer to have a rich and enjoying shopping experience, and that means providing the e-shop with modules for the co-design of products, for obtaining a smart fitting advice, and for providing high-fidelity images of the co-designed items.

3.2 myShopNET Architecture Design

One of the particularities of myShopNET platform is the integration of tools of different nature, depending of the customizable good: the same framework will support very different types of goods, like footwear, clothing, glasses, or mouth guards, even different services, like creating a movie of a fashion parade event with realistic virtual avatars and clothing.

The process of satisfying the various functionalities required involves multiple and diverse software components, namely, the myShopNET front-end, the electronic data interchange (EDI) modules, the BIVOLINO tools and services (focused on customizable shirts and blouses), the ALUGROUP tools and services (at the beginning of the project focused on customizable footwear but adaptable to any kind of personalizable product), and the CHANGE services (VaaS of high-fashion clothing).

These software components should be able to exchange information in real time using the most efficient way, to satisfy the dependences and achieve project objectives. Moreover, the infrastructure hosting the software components might exist at different physical locations which might create communication issues.

To reach these goals, the myShopNET system architecture will satisfy the captured functional and non-functional requirements specifying the logical structure of the system, giving special focus on the programing interfaces that enable the interaction and communication among the individual components (exposing their input and output methods).

Technically, to create a communication channel between the various components, an enterprise service bus (ESB) is necessary that handles the communication aspects of different protocols and data structures. This ESB is a software architecture construct, which provides fundamental services for complex architectures via an event-driven and standard-based messaging engine (the bus). Developers typically implement an ESB using technologies found in a category of middleware infrastructure products, usually based on recognized standards. The ESB takes integration's complexity out, providing connectivity to a wide range of technologies and creating services that can be reused across an organization. The ESB does not implement service-oriented architecture (SOA) but provides the features with which one may implement it. myShopNET developers can exploit the features of an ESB to integrate applications and services without creating their custom code to shield services message formats and communication protocols. Data can be transformed and exchanged across varying formats and protocols, this being a critical issue to support product-specific information standards, like the standard eBIZ [7] used by fashion business to implement the interoperability of digital communication (e-business) across the fashion supply chain.

Because of the several distinctive particularities and the need to ensure the continuous and uninterrupted data flow between the software components, an additional element has been introduced named communication framework. The communication framework undertakes the role of an intermediate service that will be responsible for data conversion and communication handling. Moreover, to maintain resources and to ensure a normal data flow, part of the communication framework's responsibility will be to organize and prioritize connection requests and connection responses.

As a summary, the whole environment components along with the software components that compose the myShopNET platform are depicted in a layered architecture, which is an instantiation of a SOA-based system reference architecture.

Following the SOA architectural pattern, the myShopNET system architecture enables the communication flow from the end user that interacts with the myShopNET graphical user interface (GUI) to the myShopNET backend services that are used to process and provide the relative information. This view can be conceptually transformed into the layered-based representation of the myShopNET architectural design.

In this layered structure, the top layer consists of the interaction layer which enables the communication with the target end users. The different components of this layer offer a graphical representation of the tools to enable the users to interact with the rest of the myShopNET platform and environment components, by using a Web browser on any type of hardware platform: PC-, Mac-, iOS-, and Android-based tablet, as well as Apple- and Android-based smartphones.

The business layer hosts the components responsible for the business logic of the myShopNET platform. This is the part of the system that encodes the real-world business rules and determines how data can be created, displayed, stored, and changed.

The data layer contains the components responsible for providing data access functionalities to the upper layer components. This object encapsulates complexity of the heterogeneous data source models for the myShopNET platform.

Both business layer and data layer are backend layers that are protected; their methods and services are not available outside of the myShopNET platform, as the platform itself only exposes the interaction and the services layers. These two layers exploit the power provided by the business and data layers exposing easy-to-use graphical user interfaces and RESTful Web services, respectively. The myShopNET layers and components are required to exchange information securely and uninterruptedly. Following on, the communication framework is introduced as the responsible communication channel for all myShopNET layers/components data interchange.

3.3 Co-design Tool

Product customization in myShopNET platform is based on the application of a schema defined by the object > parts > materials paradigm. Each object for sale can be divided into different pieces or parts, and each of these pieces can be applied to a series of materials (and complements) grouped in libraries. This allows the user to combine colors, materials, finishes, and complements to obtain an exclusive object from a multitude of possible combinations.

Centered on the virtual model of the product to be commercialized, a multi-platform (PC, Mac, tablet, Android smartphone/iOS) ICT Web application was developed in HTML 5 and supported by WebGL API. This Web application allows the buyer to customize the consumer good by choosing materials, colors, and finishes thereof for the different pieces in which each object is divided, as well as adding complements (laces, soles, buttons, embroideries, etc.).

The footwear co-designer, which is also the basis for the customization process in additional new categories of products, allows working in a real-time 3D environment, with the possibility of seeing and manipulating the shoe in three dimensions, applying materials in a very simple interface, easy to use for a non-expert user. After the customer co-design intervention, the defined model becomes a purchase order, and the purchase order becomes a production order, managed by the myShopNET platform.

As the co-design tool is a Web application, the file sizes have been minimized as much as possible, to decrease the total amount of data to be downloaded, considering that we are manipulating 3D objects that must be represented realistically, with materials with good appearance, showing not only an accurate representation of the material but also other parameters like glossiness, specularity, bumpiness, texture, and finishes.

The co-design tool works with files compatible with the FBX or OBJ standard for 3D geometry definition, with a maximum size of 100,000 triangles (and an average number ranging from 40,000 to 60,000) for the customizable consumer good, and a component list (in XML compatible format) describing the different pieces which compose each model, as well as the material combinations allowed for each piece, paired with bitmaps and shader definitions for all the materials.

3.4 Smart Sizing Tool

The main reason for most of the returns in the case of customizable clothes and footwear is the wrong choice of size by the buyer, representing a huge amount of money: $62.4bn worth of apparel and footwear are returned yearly due to incorrect fit [8]. 64% of online buyers return clothing because of incorrect fit, and 57% return footwear because of incorrect fit [9].

Related to footwear, the shoe size number is no more than a convention based on a simple dimensional rule: the size number corresponds to the useful length of the foot, considering regional variations in this size calculation. For example, in continental Europe the “Paris points” convention is used: the number of the shoe corresponds to the length of the foot in millimeters, plus 5% of space tolerance, and divided all by 6666. But the equivalence of this measure with respect to the number assigned to the shoe is where the problem lies, since the manufacturer does not make feet but shoes, based on last geometries, and the lasts (which create the inner space of the shoe during the manufacture) do not correspond exactly, from a geometrical and an anatomical point of view, with the foot.

To enhance the online shopping of customizable consumer goods, we developed sizing algorithm for clothing and for footwear (based on the use of support vector machines). These algorithms are integrated with the co-design tool in the e-shop, being able to recommend to the buyer the correct size of the co-designed consumer good, the one best adapted to her/his dimensions. In the case of footwear, the user foot size can be obtained by several different methods: a stationary 3D foot scan device coupled with a measurement software application producing up to 11 foot measures, a smartphone foot size application based on the capture of 3 images (lateral and medial with an angle that enables the capture of the foot arch and zenithal) of each feet, and cloud-based geometry reconstruction and measurement producing up to 22 foot measures or simply length measurement with a ruler and paper.

One key element of the smart sizing recommendation is because comfort is a subjective sensation, and is perceived very differently from one user to another, and even is differently evaluated by men and women in the case of footwear [10]. Because of this, footwear smart recommendation algorithm considers not only foot measures but also the type of foot (constitution with greater or lesser fat index, measure and proportion of plantar arch index, type and distribution and foot toes, relative height of the calcaneus, perimeter of ball, etc.), the type and model of the co-designed footwear, the materials used for manufacturing the shoes, and a set of subjective data involved in the perceived sensation of comfort.

The result of the sizing calculation can be applied to a size recommendation in made-to-order (MTO) goods or to a more precise adjustment in made-to-measure (MTM) ones. In the case of MTM footwear, this allows to automatically select from a matrix of model lasts, including half sizes and at least three different widths, the best one to be used for the manufacture of the most comfortable shoes for a specific user.

3.5 Visualization as a Service

The myShopNET platform includes not only tools for deployment of complete e-shops of various kinds of consumer goods but also services for sellers. And one example of the type of services which can be integrated in the platform is the Visualization as a Service (VaaS) for luxury fashion.

The VaaS is offered as an alternative to expensive luxury fashion clothing prototyping, allowing the creation of photographs and videos of exclusive limited-edition capsule collections from high-end independent womenswear designers, by using the best of fashion and film CGI technologies, including realistic virtual avatars and accurate fabric physical behavior.

Having zero prototyping, reducing product development cost, inventory risk and waste, and selling directly to the end customer result in 50% price reduction compared to designers' main line without compromise on the quality of design, fabrics, or manufacturing, allowing a more equal revenue distribution: product pricing is calculated on the basis of 3 times cost (1/3 for production, 1/3 for designers, and 1/3 for distribution) instead of the current wholesale model based on 6+ times production cost.

This new way of thinking about luxury fashion clothing will bring radical results and truly support independent designers internationally, as well as to those who value superior design and making, to change how we dress and express ourselves going forward. The objective of VaaS is to reach out to young creative and price-conscious "cool hunters" seeking alternatives to mainstream luxury fashion and its premium price.

4 Discussion and Conclusions

In summary, the main goal of project myShopNET is to provide a solution to the unavailability of online shop creation tools focused on personalized consumer goods, with the objective to increase the number of distributors that use our partners' ICT solutions to open online shops to distribute their personalizable consumer goods, increasing the number of European SMEs able to commercialize their products at the Internet with an easy-to-use tool at a very competitive price.

Right now, we have a technological solution for high-fashion shirts and footwear, easily expandable to any other customizable consumer goods, already tested with a reduced number of real users, but we need to increase momentum and accelerate the expansion.

And we also need to expand the solution to other consumer good sectors. The proposed solution is easily adaptable to any other consumer goods that share the specific requirements and solutions of personalizable items, requiring the use of co-design tools, specialized fitting and sizing tools, pre-visualization in high-fidelity image, and/or real physics behavior of the personalized items.

In fact, to replicate the model to other sectors, the only things needed are 3D/2D models of the items to be sold (digitized or modelled), component description of the goods (pieces and materials) in an open structured language (XML), and a library containing the virtual materials (digitized or created in 2D). Indeed, myShopNET platform has been designed as a solution open to any kind of objects, and there are no technical limitations for the replication and expansion of the solution to all sectors of personalizable consumer goods: fashion complements, bags, jewelry, glasses, watches, toys, furniture, etc.

Even considering the huge market opportunity, and the lack of specific tools focused on the commercialization of customizable consumer goods, it is not easy for SMEs to catch a significant position. Right now, we have four main barriers that we expect to solve with this project: to enlist key players of the e-commerce scene and create traction and visibility for the proposed solution, to expand the use of our tools and platform to other sectors, to increase the total number of users, and to clearly differentiate our solution from other generalist e-shop creation tools.

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Mass Customization Practices of Malaysian SMEs Apparel Sector: An Exploratory Survey

Rohana Zur and Syaimak Abdul Syukor

Abstract Mass customization (MC) is one of the business methods, which combines the flexibility and custom-made products, associated with mass production. Recently, this business strategy has received vast attention from industries and the academic world, but the approach is still inadequate in Malaysia especially the SMEs apparel sector. The aim of this study is to examine the MC practices in Malaysia's SMEs apparel sector besides to carry out the fundamental overview concerning the factors of MC implementation, in collaboration with the Malaysia SMEs apparel sector. The method used was survey (open-ended questionnaire) and involved participation from 343 SMEs. The preliminary analysis demonstrates that the Malaysia SMEs apparel are motivated and have intention to implement MC approach, but the overall competency of MC approach is still missing. However, the overall finding shows that the knowledge of MC significantly predicted the readiness factors $p < 0.05$, while the manufacturing process flow becomes the key indicator to look at for the MC implementation. Besides, respondents also did not see any financial issues as a major barrier for MC implementation. This will give positive prospect to emphasize this method among the entrepreneurs. Briefly, this study provides an overview in understanding the requirement, execution, and future challenges for MC implementation. It also discusses the advantages in implementing MC in the Malaysia SMEs apparel sector. Furthermore, the implementation of MC as their business strategy will encourage the companies to become more competitive.

Keywords Mass customization · Small and medium enterprises (SMEs) · Apparel sector Malaysia · Readiness

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1 Introduction

1.1 A Subsection Sample

Mass customization (MC) concept is a growing trend for manufacturing sector. This concept adheres to the needs of modern consumers and assists manufacturer to be more competitive. By providing customization option, exclusivity of the brand will increase. In addition, customization will assist companies in increasing their profit and differentiate their products from other competitors. On top of that, MC implementation is economically viable and can help to stimulate consumer interest. Although mass production is still the main method to the entire industry in the world, rapid changes in consumer behavior and progress in manufacturing process and information technology have triggered MC to become the increasingly viable approach [1]. Moreover, today's markets change swiftly, and the consumers are more demanding than ever [2]. Through MC, the customer demands to increase the integration of the supply chain that then benefits the manufacturing companies, such as less inventory and improved inventory handling and turnover, reduction in production model obsolescence, and fashion risk [3]. In addition, the productions of garments have to be planned in advance. This is to ensure that the design, style, materials, and quantity of the products are based on customers' requirements [4].

In the past decade, MC becomes prominent in many businesses. Such trend is triggered by the advancement of consumer-driven marketplace. In recent years, more SMEs companies initiate to adopt this business strategy, especially those in the field of consumer packaged goods (CPS) [5]. Successful implementation of MC in SMEs is due to close collaboration with supplier, understanding local demands, and good relationship with customers [6]. Moreover, there are also initiatives to boost the development of innovation product to reach global market by the local authority such as government, bankers, and others. Moving on, the development of MC concept has been elevated by SMEs in other Asian developing country [7]. According to the Economist Intelligence Unit Limited 2016 [8], the demand of personalization in products and services from American and European market are overtaken by East Asian countries. The general opinion is local companies have better ability than multinational companies in meeting customization demand close to consumer needs due to lower logistics costs and delivery issues [9].

In Malaysia, MC concept is relatively new among SMEs [10]. Nevertheless, "customized products" is a familiar concept among SMEs apparel industry which are highly demanded by Malaysian consumers, especially from domestic markets [11]. SMEs entrepreneurs employ conventional practices by producing tailor-made products and personalizing their services [12]. Similarly, product customization allows customers to decide on the design themselves. It can also be tailored to fit customer's body shape and preferences [11]. However, SMEs entrepreneurs seemed to have difficulty in implementing it on *mass* market. Many old habits or traditional methods and knowledge prevent the implementation and efficient use of MC [7, 13]. Although the numbers of theoretical works on MC efficiency and effectiveness are increasing, its adaptation in real-life situation is still facing many challenges internally and externally [14, 15].

Therefore, to fill this gap, this study aims to explore the main variables that affect the readiness of the Malaysia's SMEs apparel sector in MC implementation. In addition, this study will also discuss the indicators required to understand the key implementation processes of MC technique. The outcome of this research will give an overview on the use of MC technique among SMEs in Malaysia, which is lacking in previous studies. It is also hoped to contribute to MC future research.

2 Literature Review

2.1 Overview of Malaysian SMEs Apparel

According to Small and Medium Enterprises Corporation Malaysia (SMEs Corp. Malaysia), Malaysian SMEs are defined as:

- *Manufacturing sector*: Sales turnover not exceeding MYR50 million or full-time employees not exceeding 200 workers [16]
- *Services and other sectors:* Sales turnover not exceeding MYR20 million or full-time employees not exceeding 75 workers [16]

SMEs in Malaysia contribute to the country's overall economic development and become the backbone of Malaysia long-term industrial development programs [17, 18]. Apparel sector in Malaysia's SMEs that focuses in textile, leather, and footwear categories plays an active role in encouraging entrepreneurship, fostering economic activities, and creating job opportunities. According to the deputy minister for International Trade and Industry, Ahmad Maslan, the garment export climbed up to RM6.99 billion in June 30, 2016, due to the higher export orders from the United States, EU countries, and Canada [19]. Furthermore, the small-scale industries support larger industries, involve in domestic market or local consumption, and engage with export activities [20–22].

Moreover, in Malaysia, the majority of SMEs are in textiles-, apparel-, and resources-based industries. With regard to location, Saleh and Ndubisi [19] have found that a vast number of manufacturing companies in Malaysia are located in the West Coast of Malaysia whereby such locations are well known as industrial location and are equipped with ports services. It was also found that state of Johor, Terengganu, and Penang have the largest number of manufacturing companies (textiles and apparel based) due to the availability of cheap labor and logging activities in that area. Meanwhile, the majority of SMEs that are in retail and wholesale type are in the state of Selangor, Kuala Lumpur, Perak, and Kedah. These industries are comprised of two main sub-sectors which are textile (encompasses a broad range of activities such as polymerization, spinning, weaving, knitting, and wet processing) and apparel (includes garment making and clothing accessories (buttons, zippers, labels, and packaging). Data from SME Corp stated that there were about 624 apparel companies in Malaysia, as in 2015 [16]. The data also shown that state of Selangor and Kuala Lumpur have the highest number of apparel companies compared to other states in Malaysia.

However, SMEs companies in Malaysia are facing big challenges and problems in respect of their survival or in competitive advantage. According to the available resources, more than 50% of SMEs in Malaysia failed within the first 5 years of operation due to facing serious issues to stay as competitive enterprise in the market [15]. Many SME companies have been under pressure to meet conflicting goals of efficiency and consumer choice [23]. A research from Timothy, Carol, and Thomas [24] has mentioned that small firm such as SMEs needs to consider three factors, customer satisfaction, customer awareness, and brand image/position, in order to implement MC concept. Lack of consumer demand becomes the second greatest risk to the SMEs business based from the survey respondent from 15 countries including Asia Pacific [24].

Basically, SMEs apparel sector is providing customized product or services to the specific customer, but if they can offer the same concept of customized product to the mass market, then this become an advantage of doing so. With MC concept, one can enjoy all the privileged value without any significant cost and eventually at no added costs [25, 26]. Several studies have also mentioned that small business-like SME industries can easily adapt and make changes to implement this strategy effectively compared to the large industries [27]. Suzic [28] has also stated that there are a lot of success stories of the MC implementation in the SME industries due to the benefits of closer customer-supplier relationship.

However, the implementation needs to be pointed and clear, based on local study in Malaysia apparel industries. Although, there are many cases that has been studied by others countries, the involvement of this concept in Malaysia apparel industry is still lacking.

2.2 The Advantages of Mass Customization Implementation in Small and Medium Enterprises (Apparel Sector)

Despite their important contribution to the country's economy, SMEs apparel sector is facing various challenges to improve their processes, products, and services in maintaining their market dynamic [29]. Inventing uniqueness and precise consumer cohort target will encourage loyalty from consumers, and it is one of the key strategies to strong and competitive business [30]. Hence, MC is the outcome gained from self-aware customers who demand more choice and involvement [31]. MC has been identified as a competitive strategy by an increasing number of companies that is suitable with the development of SMEs itself [32]. Besides, it also promises customized products at mass production price with no purchasing delay and low inventory [33, 34]. Moreover, MC products can be put on sale before the manufacturing takes place. Below are the advantages of MC implementation in SMEs:

1. Product Variety: Offer unique and wide range of customized products and services in large scale with mass production price and maintain lower inventory.
2. Manufacturing: Improve efficiency, lower time and cost production, reduce inventory, and eliminate material waste and flexible manufacturing.
3. Marketing: Easy to deliver, products and services are market affordable with enough variety close to customers' requests.
4. Business Relationship: Gain good relationship with supplier, distributor, and customers – collaborative work to provide fast and efficient process of the customized products.
5. Sale Operation: Increase cash flow.

2.3 Mass Customization Readiness

Readiness refers to the process toward altering people's actions, reactions, and interactions to move the organization's existing state to some future desired state [35]. Readiness is important to be understood because it involves moving from the known state to the unknown state, ending the way things are done and doing things in some new ways [31, 36]. Readiness in MC is a one of the precondition requirements to change at the same time raised by the content, which, what is changing, process how change start from take place, context state where change occurred and individual their characteristics will be asked toward changes [37].

Several studies in MC implementation show that the structure of organization or firm is important to be considered for the availability of MC readiness [32, 38, 39]. This type of culture is very important in developing firm's ability to translate customer demands into products and services, especially since MC is a chain-based concept [40]. Another report by Piller [41] states that to ensure the success of MC concept, MC implementation should be determined in advance and become the fundamental feature to the organization readiness.

Therefore, several approaches must be identified in order to implement MC concept. Some authors have addressed the key indicator of MC implementation, such as "Knowledge in MC" reported by Chandra and Kamrani [38], Hirschhorn et al. [42], Gooley [43], and Suzic et al. [28]. Knowledge has been referred to support the efficient utilization of MC implementation and a good strategy for the manufacturers to satisfy the changing customer needs and desires [18, 29].

Several studies also mention the "manufacturing process" that also plays an important role to the MC implementation [7, 33, 39, 44]. Abdallah and Matsui [45] have also reported the processes in manufacturing, such as lean practices, just-in-time production, manufacturing strategy, and supplier and customer relationship management, which are also significant to MC implementation. In forward report by industrial manufacturing last year, production process becomes the key aspect for MC implementation whereby they still need to make a lot of adjustments specially to consider the design for make-to-stock assembly, where profits came from producing large volumes of identical products [46]. In other words, Piller [41] confirms that, the key readiness of MC is to align all the production processes with business management and customers' needs.

However, "skilled labor" is also required to set up the first part during the manufacturing process [17]. When MC is implemented in manufacturing process, workers in production must be able to handle all parts of the machine including 3D machine [47]. According to report by O'Reilly [31], the workers need to be trained on one specific task that performs just one function several times a day and resulting in workmanship that is more consistent. Other than that, "layout planning" of machinery, equipment, and office layout on manufacturing area become the key part for MC implementation [47]. New layout and installation of production line must be defined in firm's position space [47]. According to the Heragu and Kusiak [48], proper layout has an impact to the overall operation and can even reduce 50% of operating expenses and also can increase the amount of the organization's products and services.

Apart from that, "technology transfer" such as the Internet, software designing, and virtual products also play as powerful tools for realization of MC [26, 49, 50]. Research shows that the use of technology will result to a valuable opportunity to the development of MC implementation toward the apparel industry [51, 52]. In addition to this, Bellemare, Carrier, and Baptiste [51] have confirmed that many apparel businesses are currently exploring technology transfer that will give better performance on production process and consumer inputs.

Besides this issue, Chandra [38], Gooley [43], and Taylor et al. [22] have pointed out that the "management" should also play an important role in MC implementation. The link between internal and external management (logistic, operations, distribution, and marketing) needs to be strong in order to implement MC concept successfully. Otherwise, the MC products offered will be inadequate in the market or too costly in operational terms [33].

The importance of "product knowledge" for MC implementation catches the attention of many researchers [4, 11]. The trend now is toward a customer who wants to be personalized [53] and loves to be guided, to be directed, to be recommended, to be advised, or to select the best options regarding the product or services. Having an understanding about the customized products will allow the retailer to use different methods of presenting the products to the customers. Therefore, to implement MC concept, company should prepare training on product knowledge to the related staff, in order to understand the key importance of MC concept and benefits to the customers.

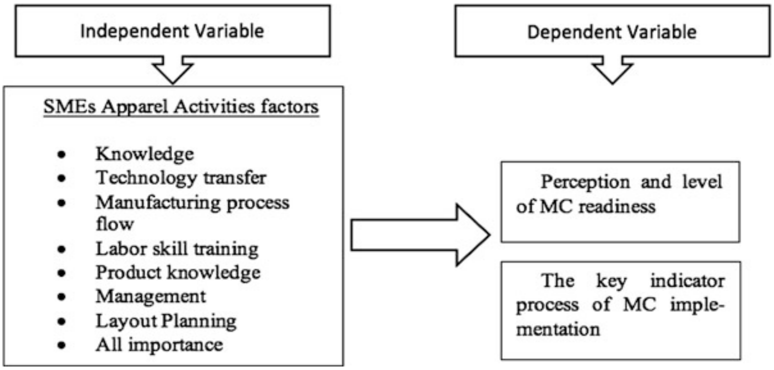

Fig. 1 Research framework

3 Research Framework

The research framework for this study is shown in Fig. 1, whereby the eight independent variables, namely, knowledge, technology transfer, manufacturing process flow, labor skill training, product knowledge, management, shop layout, and all importance, were tested against the readiness of MC implementation.

4 Methodology and Data Analysis

This empirical study was conducted to obtain feedback from companies. The respondents were selected from companies from all the states in Malaysia that are registered with SME Corp Malaysia and run the apparel business. Due to an agreement with SME Corp Malaysia, the list is confidential.

Survey was done randomly using survey instrument via phone. Then, the respondents were guided and assisted in answering the survey to ensure that the respondents understand the questions. The advantages of using phone survey are a fast method, target specific respondents, and give access to a large scale of respondents [54]. Moreover, majority of people respond in a more positive manner when speaking than when they are replying the questions in writing. The set of questionnaires used in this study contained an open-ended question that helped to determine the two factors: the level of readiness and the level of understanding of the key implementation processes of MC technique. The feedbacks were helpful to improve the understanding of the main issue. Then, the data were analyzed through simple regression and multiple regression method using SPSS version 12.

Taking into account the importance of MC among SMEs apparel industries, all respondents have sufficient work experience; most of them are supervisors, managers, or owners of the SME company itself. The managerial or organizational leader's implication of the assessment is the first step in discussing the viability of MC strategy which brings together to discuss the strengths and weaknesses of the main issue [29].

Before performing parametric analysis, normality test was assessed using the skewness and kurtosis. Hair et al. [55] and Bagozzi and Yi [56] have reported skewness and kurtosis values provide a more accurate measurement of normality. The results in this study indicated that there were no values exceeding the acceptable range of skewness as suggested by Hair et al. [55], which is between −2.58 and +2.58 at the 0.01 significance level or between −1.96 and +1.96 at 0.05 significance level. As for kurtosis, the normal range is between −3 and +3 (Table 1).

According to Hair et al. [55], the assumption of multicollinearity can explicate variable in the analysis. The challenge in clarifying the impact of any single variable owing to their relationship is explained by multicollinearity. In this analysis, the results obtained indicated that multicollinearity does not exist among all independent variables because tolerance values are more than 0.10 and VIF values are less than 10. Therefore, the study does not have any problem with multicollinearity (Table 2).

Table 1 Validation and reliability using normality test

	Skewness	Std. error of skewness	Kurtosis	Std. error of kurtosis
Knowledge	−0.67	0.13	−0.75	0.26
Readiness	−0.80	0.13	−1.21	0.26
Technology transfer	0.31	0.13	−1.91	0.26
Knowledge of MC	−0.06	0.13	−2.01	0.26
Manufacturing process	0.33	0.13	−1.90	0.26
Labor skills training	0.59	0.13	−1.66	0.26
Product knowledge	0.69	0.13	−1.54	0.26
Management	0.94	0.13	−1.13	0.26
Layout planning	1.86	0.13	1.47	0.26
All importance	−0.39	0.13	−1.86	0.26

Table 2 Validation and reliability using multicollinearity

	Collinearity statistics	
Construct	Tolerance	VIF
Technology transfer	0.26	3.90
Knowledge of MC	0.40	2.51
Manufacturing process	0.34	2.95
Labor skills training	0.35	2.84
Product knowledge	0.24	4.16
Management	0.28	3.51
Layout planning	0.62	1.62
All importance	0.44	2.28

Table 3 Simple regression based from "readiness"

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. error	Beta		
(Constant)	0.038	0.072		0.519	0.604
Knowledge	0.979	0.041	0.792	23.952	0.000

Dependent variable: readiness
$DF_{1,341} = 573.695$, $p < 0.05$ ($R2 = 0.63$)

5 Result and Discussions

Simple regression was used to determine the effects of knowledge toward readiness, while multiple regression was conducted to examine the relationship between sets of independent variables (technology transfer, knowledge of mass customization, manufacturing process flow, labor skills training, product knowledge, management, shop layout, and all importance) toward readiness to implement the concept of mass customization (MC).

The result from the regression analysis demonstrated that knowledge has significant effect toward the readiness ($DF_{1341} = 573.695$, $p < 0.05$). The overall model has shown 63% variance changes in readiness. Looking at the beta in every one-unit changes in knowledge, change of 0.979 is expected in readiness (Table 3). Hence, knowledge is an important factor in determining the readiness of the companies in implementing MC concept. Furthermore, readiness is a necessary precondition for a person or an organization to succeed in facing organizational change [19]. In other words, the success of the MC implementation depends on the knowledge among the members, and it will significantly affect their readiness to do so. These can be considered as the main factors and prerequisite for MC implementation.

Next, respondents also perceived technology transfer, knowledge of mass customization, process manufacturing flow, labor skills training, product knowledge, management, and shop layout as important factors to prepare for MC implementation. Multiple regression analysis was used to determine significant predictors toward readiness. The model of regression produced significant results ($DF_{8334} = 51.838$, $p < 0.05$). It was found that knowledge of MC ($B = 0.47$, $P < 0.05$) and all importance ($B = 0.78$, $p < 0.05$) were the significant factors toward the readiness of MC concept implementation (Table 4). It was noted that all indicators listed were important factors. Nevertheless, the main indicator is the knowledge of MC and manufacturing process flow.

6 Future Direction

The empirical results demonstrate how the knowledge of mass customization (MC) affects the readiness level among SMEs apparel in Malaysia. It has proven that the identified variable set of indicators – technology transfer, knowledge of MC,

Table 4 Multiple regression based from the set of independent variable

Model	Unstandardized coefficients B	Unstandardized coefficients Std. error	Standardized coefficients Beta	t	Sig.
(Constant)	1.57	0.05		30.44	0.00
Tech transfer	0.16	0.13	0.09	1.30	0.20
Knowledge of MC	0.47	0.10	0.27	4.67	**0.00**
Manufacturing process flow	0.06	0.11	0.03	0.51	0.61
Labor skills training	0.06	0.11	0.03	0.52	0.60
Products knowledge	0.07	0.14	0.04	0.50	0.62
Management	*−0.13*	0.13	−0.07	−0.99	0.32
Layout planning	*−0.03*	0.11	−0.01	−0.26	0.79
All importance	*0.78*	0.10	0.44	8.02	**0.00**

Dependent variable: readiness
$DF_{8334} = 51.838$, $p < 0.05$ ($R2 = 0.55$)

manufacturing process flow, labor skills training, product knowledge, management, shop layout, and "all importance" – also have significant relationship to the SME readiness. However, the knowledge becomes the key importance after manufacturing area. Moreover, guidelines in applying MC and a framework that enhances its usage should be established. This study contributes to the literature and practitioners particularly to the small- and medium-sized companies especially in apparel sectors, as well as SME Corporation as a policy-maker. Additionally, future studies are recommended to explore the standard operating procedure (SOP) in manufacturing area that is one of key importance toward the MC implementation. Moreover, an exploration on MC modules that is tailored to SMEs apparel in Malaysia is another possible direction to take.

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Attitudes Toward Apparel Mass Customization: Canadian Consumer Segmented by Lifestyle and Demographics

Hala Hawa

Abstract The widespread of the Internet and mobile applications among consumers made it possible for them to access markets otherwise inaccessible. Manufacturers became able to reach consumers directly, thus reshaping their shopping experience. Technological advances in apparel manufacturing and e-commerce made apparel mass customization available to consumers online.

Online clothing sales are rising in Canada and the USA, and so is the trend of customizing and personalizing products. However, relevant studies on consumer attitude and adoption and lifestyle segmentation are very limited in general and missing the Canadian market. Moreover, none included dress social tendency as segment.

This qualitative study is the first to explore the uptake of apparel mass customization online by Canadian consumers and identifies its ideal target market using multilayer consumer segmentation. This multilayer segmentation is also the first to apply the dress social tendency theory in conjunction with clothes shopping behaviour and demographic data that includes body mass index (BMI).

Data collection methods include an interview and a questionnaire. The sample consists of thirteen (13) participants, aged 21–65, 8 females and 5 males, from various cultural backgrounds, all residents of Ottawa, Canada's capital.

This study provides Canadian consumer attitudes toward apparel mass customization and identifies characteristics of its ideal target market. Its methodology and findings contribute as the basis for a large-scale quantitative study applicable to various global markets including that of Canada. The findings would be of interest to apparel mass customization management and marketing executives and user experience researchers and designers.

Keywords Attitudes · Consumer segmentation · Social tendency · Shopping behaviour · Apparel mass customization · Canadian consumer · BMI

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1 Introduction

The widespread of the Internet and mobile applications among consumers made it possible for them to access markets otherwise inaccessible. Manufacturers became capable of reaching consumers directly, thus reshaping their shopping experience.

Technological advances in apparel manufacturing and e-commerce made clothes shopping available online to mass markets across the globe. Selected brands pioneered selling custom clothing online after seeing success in mass-produced clothing.

Studies on consumer attitudes toward apparel mass customization are limited, and those that exist were conducted in Europe, the USA, Asia, and Saudi Arabia, hence missing Canada. Canada would be an interesting market for custom clothing due to the following factors. Its population is multicultural and composed of over 200 ethnicities [1]. It has a population of 36 million [2] and is seeing a decent growth of 7.5% [3] resulting from immigration. In addition to their variety of cultural background, over third of them is considered overweight (BMI > 25) across age and gender [4], a fact on the rise [5]. The latest statistics showed Canada's clothing online sales has grown by 9.9%, representing 4.5% of its total retail online sales [6]. These facts show a population in need of a wide range of clothing size and taste, all of which could be accommodated by local and global apparel mass customization enterprises.

The concept of apparel mass customization has the potential of meeting the needs and wants of Canadian consumers underserved by the mass-produced clothing market. This study investigates its potential adoption by a small sample of Canadian consumers and further examines its ideal target market. It focuses on consumer attitudes and their willingness to pay and wait for clothing they customized and personalized online. Furthermore, it applies a novel multilayer consumer segmentation method to help identify the ideal consumer for this concept. This method introduces for the first time the use of dress social tendency as a consumer segment, in conjunction with clothes shopping behaviour, demographics, and BMI (body mass index) by both genders.

This study uses two methods to collect consumer data: an interview and a questionnaire. The sample consists of thirteen (13) participants, aged 21–65, 8 females and 5 males, all residents of Ottawa, the capital of Canada. It contributes unique data on Canadian consumer attitudes toward this concept, and its ideal target market using novel multilayer segmentation. Its methodology forms the basis for large-scale quantitative study, applicable to any market. It would be of interest to apparel mass customization management and marketing executives, as well as user experience researchers and designers.

2 Literature Review

The following investigates apparel mass customization literature focused on consumer attitudes and willingness to pay and wait and segmentation that includes shopping behaviour, dress social tendency, gender, and BMI.

2.1 Attitudes

Majority of apparel brands selling custom clothing online are based in Germany and the USA, and some deliver globally. While most focus on custom prints onto t-shirts, few offer made-to-measure clothing primarily for men [7]. Apparel customers in various countries such as the USA [8–10], Germany [11], Saudi Arabia [12], China [13], Taiwan [14], and South Korea [15] seem interested in customizing their clothes online prior purchasing. This trend is predicted to rise in the USA [16]. However, Schoder and Haenlein (2007) argued despite consumers' interest in this concept what they value most is customization levels of the end product [13]. Furthermore, consumer attitudes toward this concept are influenced by two personal skills: first, having confidence in their ability to design [10] and, second, possessing necessary computer skills to navigate related website and design toolkit [8].

Although female consumers, in the USA, showed interest in custom apparel website' competency (the number of design options) and usefulness, they were concerned with personal information security [17], whereas adult consumers, in Sweden, had a "great experience" customizing knitted clothing interacting with a digital application at retail and coached by sales people on site [18].

2.2 Willingness

Consumer readiness to adopt customizing clothing online is signalled by their willingness to pay extra and wait longer than at retail. Though limited in volume, the following shows a positive indication.

Willingness to Pay Extra Studies in various countries show most apparel shoppers were willing to pay more than retail price to customize and purchase clothing online. While adult shoppers, in the USA, were ready to pay 20% more [16], university students would pay proportionally more for higher customization level [8], whereas in Germany, university students would pay proportionally more the higher creativity allowed within the design toolkit [11]. Similarly, adult women shoppers in South Korea were simply ready to pay more [15]. Considering shopping behaviour segmentation, Chinese hedonic university students were willing to pay more; however, utilitarian students were neither interested nor willing to pay more [13].

Willingness to Wait Most consumers were willing to wait 2 weeks for custom clothing online. This includes American adult shoppers [8], Chinese university students [13], and adult women in South Korea [15]. However, Chinese university students who followed fashion were unwilling to wait [13]. This shows a variance when considering shopping behaviour as a segment.

2.3 Consumer Segmentation

The following review addresses consumer segments relevant to apparel mass customization.

Shopping Behaviour Consumer shopping behaviour is an important data that informs apparel mass customization industry; however, limited relevant data seems available. To this end, a qualitative study on Chinese university students found hedonic shoppers were interested in customizing clothing online, while utilitarian shoppers were not [13].

Social Tendency Clothing differentiates between social classes, and individuals use it to assert their position in the society. However, changes in social conditions lessened its significance as a symbol of social status and is used more now as a communication tool to express individuals' personal identity and/or belonging to a subculture [19]. The social tendency theory that made further association between clothing and their wearer's identity results as follows: a person dresses to stand out and express their individuality among peers (out-group) or blend in with them and affirm their belonging (in-group) [20]. This type of consumer segmentation seems relevant to apparel mass customization market; however, it has not been applied to date.

Gender Gender difference in apparel shopping has been examined by various studies [21–24] however not in apparel mass customization. The collective outcome showed a gender difference in apparel shopping behaviour, and this varied based on cultural context. Although men and women seem to exhibit different behaviour toward clothes shopping, the outcome of recent studies showed men tend to be similar to women in the use of clothing to manage their appearance. For example, both prefer looser clothing as they become overweight [25–28]. Gender difference in consumer segmentation seems relevant to apparel mass customization but missing.

BMI Body mass index (BMI) is a statistical formula derived from a person's height relative to their weight. The outcome is categorized as underweight, normal, overweight, and obese [29]. Although BMI and clothing fit issues do not correlate directly, there is evidence it does with some clothes sizes [30].

2.4 Summary

Consumers' attitude toward custom clothing online seems positive, as they are willing to pay extra and wait longer for it. Available data covers various countries; however, to date none included Canada.

Data on the ideal consumer interested in customizing clothing online is limited, and primarily includes basic demographic. Consumer shopping behaviour was briefly addressed; however, none included BMI, gender difference, or dress social tendency.

This study aims to address the gaps in literature mentioned above. It explores Canadian consumer attitudes and willingness to adopt customizing clothing online, by unique multilayer segmentation. Such segmentation consists of consumer demographic data that includes BMI, in conjunction with lifestyle data that includes shopping behaviour and dress social tendency.

3 Research Method

Consumer attitude is measured based on the theory of "reasoned action". This theory states future human behaviour can be predicted by their intentions, a byproduct of their attitudes [31]. Consumer attitude toward a topic is measured by their corresponding positive (like) or negative (dislike) feelings [32].

The sample consisted of thirteen (13) Ottawa residents (5 male, 8 female), aged 21–65, between February and March 2015. They included working professionals and university students (graduate and undergraduate).

Characteristics of the target consumer are obtained applying the segmentation method [33]. Multiple segments are considered: lifestyle and demographic. Lifestyle includes consumer shopping behaviour (hedonic (H), utilitarian (U)) and dress social tendency (group (G), individual (I)). Demographic includes gender, age, education, cultural background, and BMI (body mass index). To achieve this participants data is collected in three categories (lifestyle, adoption, personal data) using two methods (interview, questionnaire) as follows:

Lifestyle Data (Interview)

1. Clothes shopping behaviour
2. Dress social tendency

Adoption Data (Interview)

3. Attitude (like and dislike) toward customizing clothing online
4. Willingness to pay extra
5. Willingness to wait

Personal Data (Questionnaire)

6. Gender, age, education, cultural background
7. Height and weight (to determine BMI)
8. Common clothes fit issues

Table 1 Lifestyle segmentation

Category	Code	Acronym	Description
Clothes shopping behaviour	Hedonic	H	Shop for pleasure
	Utilitarian	U	Shop based on need
Dress social tendency	Group	G	Blend in peer group
	Individual	I	Stand out from peer group

Table 2 Shopping behaviour segmentation by gender

	U (Utilitarian shopper)	H (Hedonic shopper)	Total
Male $n = 5$	4	1	5
Female $n = 8$	5	3	8
Total $n = 13$	9	4	13

Data collected during the interview is transcribed, clustered, and coded per participant per question and analysed based on the theories listed above. Clothes shopping behaviour is coded hedonic (H) or utilitarian (U), and dress social tendency data is coded group (G) or individual (I) (see Table 1).

Participants' personal data collected in the questionnaire is tabulated, and BMI calculated and coded per Health Canada's classification [29]. This data is then cross-examined with the interview per participant. This process identified consumer multilayer segment per response.

4 Data Analysis

Data analysis findings and insights are organized in three areas: participants' multilayer segmentation, followed by attitudes, and willingness to pay and wait.

4.1 Participants' Multilayer Segmentation

Participants (13) were diverse in gender, age, and BMI. They included eight (8) females and five (5) males, aged 21–65, with BMI classified as under, normal, and overweight [29]. They included professionals working at various industries (computer technology, science, business, engineering, geography, arts, and human resources) and university students (graduate, undergraduate). Typical of Canadian population in major cities, they came from diverse cultural backgrounds (Canada, Europe, India, Middle East, Asia, Africa, and the Caribbean). Participants' responses to clothes shopping behaviour questions showed more utilitarian (U) (9/13) than hedonic (H) (4/13) shoppers (see Table 2).

Table 3 Social tendency segmentation by gender

	I (Individual dresser)	G (Group dresser)	Total
Male $n = 5$	2	3	5
Female $n = 8$	3	5	8
Total $n = 13$	5	8	13

Table 4 Multilayer segmentation by gender

G/U	I/H	G/H	I/U	Total
Group dresser and utilitarian shopper	Individual dresser and hedonic shopper	Group dresser and hedonic shopper	Individual dresser and utilitarian shopper	
3/8 F 3/5 M	3/8 F 1/5 M	2/8 F 0/5 M	0/8 F 1/5 M	8 females 5 males
6	4	2	1	$n = 13$

Majority of the participants (8/13) dress to fit in with peers (in-group) and is referred to as group (G) segment. The balance (5/13) dress to stand out from peers (out-group) and is referred to as individual (I) segment (see Table 3).

Layering participants' social tendency and shopping behaviour results (see Table 4) produced the following four multilayer consumer segments:

1. Group/Utilitarian (G/U) (6/13): Dress to blend in with peers, and purchase clothing based on need.
2. Individual/Utilitarian (I/H) (4/13): Dress to stand out from peers, and purchase clothing based on enjoyment.
3. Group/Hedonic (G/H) (2/13): Dress to blend in with peers, and purchase clothing based on enjoyment.
4. Individual/Hedonic (I/U) (1/13): Dress to stand out from peers and purchase clothing based on need.

4.2 *Consumer Attitude*

The participant's interview responses revealed most (8/13) had prior experience in customizing their clothing; however, their experience varied by gender. Most men have had experience at retail with the help of a professional tailor, and few (2/5 M) customized clothing online interacting with the website's design toolkit. In contrast, most women have had experience making their own clothes interacting with physical design tools such paper patterns, fabric, notions, and sewing machine.

All participants regardless of gender expressed positive feelings, such as feeling "great", "rewarded", and "in control" of design decisions. During the interview, the participants were asked to share their likes, dislikes, and how they felt about customizing their clothes online. Based on their responses, their attitudes were either positive (like) or negative (dislike). The findings showed most liked "making design decisions" across all segments and most disliked "time" required during the traditional customization process; these belonged to the G/U and I/H segment.

Few participants (2/5 M, 0/8F) purchased custom shirt online. It was not surprising that they happen to be males, since apparel mass customization brands target and cater to them. The younger participant (21 yrs., business student) was considered novice at customizing his clothing, as his online experience represented his first. He expressed positive feelings and excitement toward codesigning his shirt using a mobile application. He was happy with the ease of using the website's design toolkit, number of design options, colour and patterns, and the end product (shirt's fabric, fit, and colour). He tried this revolutionary way of customizing clothing because the shirt's brand offered "no risk" two-way free shipping service. He enjoyed the simple video application for body measurement (1-min duration), the seamless ordering process, and the delivery within 2 weeks. He expressed pride in his achievement (designing his own shirt) and was thrilled to share his success story with his friends. He described his experience as follows:

> They [the brand] actually fit the shirt to you using a phone app., it is absolutely great, it is awesome. It allows you to pick the collar, pick your cuffs whether it is one button or two . . . pick the bottom of the shirt whether it is long or straight, and pick the fabric and the pattern as well. They give you a mock up of what is going to look like, and then you actually you get to see when it comes in the mail. The choices I love to make the different cuffs, the collar . . . the pattern. ...To be honest nothing to dislike really because it is so new, may be if I kept using it I wouldn't. Their consumer service is phenomenal, it is delivered to my door in good time (2 weeks) and it could have taken forever, umm, to be honest the experience was really good (22 yrs. I/U male, normal BMI, early adopter).

In contrast, the older participant (33 years old) had extensive experience in buying custom clothing at retail and briefly tried it online. Similar to the younger participant above, he liked making "design decisions" and "personalizing" his clothes to fit his body size and taste. Although he liked the customizing process, he expressed issues at retail and online. At retail his challenge was finding a good tailor that understood his vision, and reducing the fitting visits. Once he achieved the perfect fit, he had tendency to spend more on additional items to save time and money in the future. The issues he encountered online were related to the brands' presentation of the shirt's fabric quality, actual colour, and instructions for body measurements. He described his experience as follows:

> First issue online I faced is the material quality . . . the problem is . . . the colour is either lighter or darker it is not like how you see it on the screen, and the material quality, it tends to be different [than expected]. When it comes to design and customization ... measurement is a big big issue online . . . instructions need to be very clear on how to do them, and why (33 yrs. I/H male, high BMI, fashion conscious).

Similar to the male participants' experiences described above, female participants liked making codesign decisions. One female participant, who had experience in making her own clothes, described the creative process as "rewarding", but disliked the "effort" and "cost" involved:

> I do like it. You get to choose everything. You get to choose the fabric... the pattern, and... even modify the pattern a little bit... just the creative decisions are pretty rewarding. [Dislike because] it takes a lot of effort and ... it's actually not cheaper, these days it's actually more expensive, fabric is pretty expensive (41 yrs. G/H female, high BMI, tall).

Another female participant, who made her own clothing, described her experience as "fun". Similar to the young I/U male above, she was "proud" to show and tell her friends that she made it; and similar to the G/H female above, she disliked the "cost", "time", and feared "making mistakes" due to her "lack of experience". She described her likes and dislikes as follows:

> The idea of creating something, and it was fun to make, something practical that I can actually use, and kind of show other people that I've made it.... And it was fun to pick up the fabrics... it was fun to being part of the creating process. [Because] I was creating something... I was in charge, I got to show it off a bit to... friends, and ... they would say where did you got that?? Oh... I made it. [Dislike it because] it's time consuming... and [I] make mistakes... go back and fix...buy a lot of extras... like the colour thread... elastic band...buttons, the notions etc. (41 yrs. G/U female, normal BMI).

Lastly one female participant, who has experience customizing clothing at retail with a tailor, expressed "pride" in her creation. She credited her tailor for quality product that matched her vision. Similar to others above, she disliked the "time" to produce a tailored piece of clothing:

> My tailor is very good, I am rest assured that she will get the style, she is not going to mess it for me, and it is going to fit appropriately. I know that when I wear something from her people always ask me where I got it. [Dislike it because] it takes a lot of time (2–4 weeks)... is major disadvantage (25 yrs. I/H female, normal BMI, fashion conscious).

In summary, participants across gender liked the concept of customizing and personalizing their clothes online. They liked being in control of design choices and felt "proud" to show off their creation to friends. They disliked the "cost" and "time" required at retail by the tailor or at home by themselves. However, those who codesigned a shirt online had different experience. The novice participant rated his experience as highly positive; by contrast, the experienced participant did not express positive feelings due to misrepresentation of clothing material, quality, and colour on screen and unclear body measurement instructions. The online experience seems dependent on the brands' experience and participant's knowledge and expectations.

4.3 Willingness

Participants' intention to adopt custom clothing online was gauged by their willingness to pay extra and wait for its delivery.

Willingness to Pay Extra When the participants were asked how much more than retail price would they be willing to pay for custom clothing online, most (11/13) were willing while few (2/13) were not. Their responses were segmented into three categories as follows:

- Category 1: –50–0% (unwilling)
- Category 2: 10–60% (willing)
- Category 3: 100–250% (willing)

To further understand those willing to pay more for this concept, the above categories were cross-examined with their personal data collected from the questionnaire. The results are listed below per paying category:

Category 1: Few participants (2/13, 2F/0 M) although interested in the concept were unwilling to pay more for it. These participants shared similar characteristics. Both were female, I/H segment, had low BMI, and limited income (retired, student). Below are excerpts of their interview responses:

> Because fast fashion is so tempting and so inexpensive . . . I don't spend a lot of money today. Years ago I did but now that I am retired, I have all the suits I need in the world (65 yrs., I/H, low BMI, fashion conscious).

And

> Knock off high fashion with cheaper material hopefully 50% less expensive. It really depends on my own want . . . if there is an item of clothing I really want from an expensive store . . . like $300 or $400 . . . I might do custom clothing to have the same design and look and maybe cheaper material so it would be cheaper overall (21 yrs., I/H, low BMI, fashion conscious).

Category 2: Most participants (8/13, 4 M/4F) across all multilayer segments were willing to pay 10–60% extra. Their reasons included better body fitted clothing, higher-quality fabric and execution, and control over realizing their vision. Some were ready to pay more for higher level of customization and special occasion (wedding, etc.). Below are excerpts of their interview responses:

> [Willing to pay extra] because the quality would be better, the personalization will be there... 10% to 20% max for customizing the size, and rest for better quality and personalization (33 yrs., I/H male, high BMI, fashion conscious).

And

> [Willing to pay extra] 50%–60% [for major events]...depends on what I am customizing [clothing] . . . would have different prices . . . major event . . . more expensive than customizing for something [not major] . . . Depends on the material and on the style (25 yrs., I/H female, normal BMI, fashion conscious).

And

> [Willing to pay extra] 30%–40% . . . because I realize the result would probably be a lot better [than if I made it] ... It's not really a priority for me . . . I would do [it] for special occasions or . . . something really specific . . . that I couldn't find in stores (41 yrs., G/H female, normal BMI).

Category 3: Three G segment participants (3/13, 1 M/2F), across gender and shopping behaviour, were willing to pay 100%–250% more than at retail. This is considerably more than category 2 above was willing to pay given similar reasoning.

Cross-examination of their personal data showed one or more of the following characteristics by participant: high BMI, above average height, overweight, untypical body shape (pear shape), and quality conscious, inspired by celebrities. Below are excerpts of their interview responses:

> An average suit . . . probably cost around . . . $600 . . . I'll be more than willing to pay 2 1/2 times that for a [custom] suit . . . my reasoning would be...it's what the people [celebrities] that inspired my fashion sense would be wearing . . . [also] Knowing that what you bought is high quality as well . . . you know material matters, I would be willing . . . [to] splurge on that a little bit (21 yrs. G/U male, high BMI, tall and over weight).

And

> [If] I customized [a dress] and . . . it was perfect exactly the way I wanted it, then I would say [am willing to pay] maybe double or may be a little less (24 yrs. G/H female, normal BMI, pear shaped body).

And

> It depends on the degree of customization...If it would be customizing . . . either the colour or the cut or the sleeves or the collar or anything like that . . . I would be willing to pay 50%–80% more...If it is customized completely to me I would be willing to pay 100%–150% more (24 yrs. G/U female, normal BMI, quality conscious).

Cross-examination of paying categories mentioned above with multilayer segmentation showed category 1 belonged to I/H segment: female (student, retired) with low BMI, was unwilling to pay more. Category 2 belonged to all multilayer segments, was willing to pay more. Finally category 3 belonged to the G segment across shopping behaviour, most had untypical body characteristic (pear shape, overweight) and quality conscious, was willing to pay substantially more (see Table 5).

Willingness to Wait Participants were ready to wait maximum 2–4 weeks for clothes they customized and purchased online. This data is segmented into three levels based on number of weeks. Cross-examination of these levels with multilayer segmentation shows level 1 participants belonged to G/U and I/H segments were willing to wait maximum of 2 weeks. Level 2 participants belonged to G/U I/H and I/U segments were willing to wait maximum of 3 weeks. Finally, level 3 belonged to G/H and G/U segments were willing to wait the longest of 4 weeks (see Table 6).

Table 5 Willingness to pay by multilayer segment

Category	Pay range (% > retail price)	Multilayer segment	Gender
1	(50%)–0%	I/H, Low BMI Limited income	2/8 F 0/5 M
2	10–60%	G/U, G/H, I/H, I/U	4/8 F 4/5 M
3	100–250%	G/U, G/H Untypical body shape High BMI Quality conscious	2/8 F 1/5 M

Table 6 Willingness to wait

Level	Wait (weeks)	Multilayer segment	Gender
1	2	G/U, I/H	3/8 F 3/5 M
2	3	G/U, I/H, I/U	2/8 F 2/5 M
3	4	G/H, G/U	3/8 F 0/5 M

5 Conclusion

The preliminary findings of this qualitative study suggest potential adoption of apparel mass customization by Canadian consumers with few concerns. All participants (13) expressed positive attitude toward this concept highlighting their control over design decisions. Their areas of concern were related to the following: cost, time, and effort required, user experience, trusting the overall quality, and colour of the end product. Most were willing to pay extra, and all were willing to wait for it.

The ideal Canadian target market for customizing clothing online is identified using a multilayer consumer segmentation approach. The greatest potential in adopting this concept was found in less than half the G segment (G/U and G/H), across gender. These participants are willing to pay significantly more and wait significantly longer for custom clothing online. In addition to being quality conscious, they have physical challenges such as being overweight, above average height, and untypical body shape.

In addition to the ideal target market listed above, there is a certain degree of interest in custom clothing online across all multilayer segments, as they were willing to pay extra for it. Their motivation is realizing own vision and exercising their creativity. However, those identified as I/H females with low BMI and limited income, although interested, they would only be willing to engage if they pay regular or discounted retail price.

These findings further the understanding of the apparel consumer in Canada. They are of interest to apparel mass customization enterprises, their management and marketing executives, and their researchers and user experience designers. In addition, the multilayer consumer segmentation approach would be applicable to all industries offering customized and personalized products and services.

Recommendations Based on the results, it is recommended to conduct large-scale quantitative study to generalize the preliminary findings and multilayer consumer segmentation approach. This will further identify the ideal target market for customizing apparel online in Canada and globally. This segmentation approach is also applicable to other industries implementing the mass customization and personalization concept.

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In the back cover of the book, the chapter title in the Open Access licence text has now been corrected to be 'An Evaluation Model for Web-based 3D Mass Customization Toolkit Design'

In addition, an incorrect open access license logo was applied at the end of Chapter 23. This has now been corrected to display the correct logo of CC BY.

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